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Legumes in Cropping Systems

Edited by **Donal Murphy-Bokern**,
Frederick L. Stoddard and **Christine A. Watson**



LEGUMES IN CROPPING SYSTEMS

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Preface

Europe is self-sufficient in most major agricultural commodities and a net exporter of some, particularly cereals. This remarkable productivity has come at a cost for the environment and is associated with imbalances in European cropping systems, manifest in particular by the low use of legumes. By 2010, when the Legume Futures project was initiated, this imbalance was already a concern in the mainstream agricultural policy community. This book is aimed at supporting informed debate and decision making that addresses the resulting challenges.

Legume crops are neither good nor bad in themselves, so this book is not advocating their use. It is a contribution to the debate and knowledge for the rebalancing of farming and food-using legumes. The main aim is to help people who are involved in developing cropping systems: the decision makers of today and today's students who are the decision makers of tomorrow. It is aimed at all relevant decision makers: farmers, professionals who support innovation in farming, and the policy community in its widest sense. The core of the book is 13 chapters describing various aspects of the use of legumes in European cropping systems. In each chapter, the authors provide deep insight into the relevant literature to support understanding rather than a comprehensive academic review. The aim is to empower the reader with insights and understanding of the underlying processes that influence cropping system development.

While most of the authors were supported by the European Union through the Legume Futures consortium, many others contributed. We are particularly grateful to the following for their contributions: Michael Abberton, Paolo Annicchiarico, Isabella Badenhauer, Jessica Capraro, Imelda Casey, Gilles Crocq, Jens Dauber, Jean-Claude Emile, Daniel Enriquez-Hidalgo, Georg Everwand, Fredrik Fogelberg, François Gastal, Eric Guillemot, George Hill, Bernadette Julier, Denis le Chatelier, Gaëtan Louarn, Alain Peeters, Udo Prins, Jürgen Recknagel, Alessio Scarafoni, Henk Westhoek, Michael Wink and Lana Zorić.

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Abbreviations

ADF	acid detergent fibre
AES	agri-environment scheme
BNF	biological nitrogen fixation
BSE	bovine spongiform encephalopathy
C	carbon
CAP	Common Agricultural Policy
CAPRI	Common Agricultural Policy Regional Impact
CHU	crop heat units
CLA	conjugated linolenic acid
CLIMA	Centre for Legumes in Mediterranean Agriculture
CO₂	carbon dioxide
CP	crude protein
DDGS	dried distillers grains with solubles
DM	dry matter
€	Euro
EC	European Commission
ECPGR	European Cooperative Programme for Plant Genetic Resources
EFA	ecological focus area
EU	European Union
EU-6	the original six members of the EU: Belgium, France, Italy, Germany, Luxembourg and the Netherlands
EU-9	The EU-6 plus Denmark, Ireland and the UK
EU-27	The EU with 27 member states before Croatia joined
EU-28	The current EU, including Croatia
FAO	Food and Agriculture Organization of the United Nations
GATT	General Agreement on Tariffs and Trade
GDP	gross domestic product
GHG	greenhouse gas
GM	genetically modified
ha	hectare
HLY	healthy life years

INRA	Institut National de la Recherche Agronomique
IPCC	Intergovernmental Panel on Climate Change
K	potassium
kg	kilogram
LAI	leaf area index
LCA	life cycle assessment
LER	land equivalent ratio
LfL	Bavarian State Institute for Agriculture
LGM	legume-based green manure
ILTER	Long Term Ecological Research (network)
MGA	maximum guaranteed area
MS	member state
N	nitrogen
NGS	next generation sequencing
N₂O	nitrous oxide
NSP	non-starch polysaccharide
NUE	nitrogen use efficiency
NUTS	Nomenclature of Units for Territorial Statistics
OECD	Organisation for Economic Co-operation and Development
P	phosphorus
PAHs	polycyclic aromatic hydrocarbons
PAR	photosynthetically active radiation
PGREFA	plant genetic resources for food and agriculture
ppbv	parts per billion by volume
PPO	polyphenol oxidase
PRG	perennial ryegrass
PUFA	polyunsaturated fatty acid
QA	quinolizidine alkaloids
QTL	quantitative trait loci
RAD-seq	restriction-site associated DNA sequencing
RDP	Rural Development Programme
SAPS	Single Area Payment Scheme
SBM	soybean meal
SGSV	Svalbard Global Seed Vault
SPS	Single Payment Scheme
t	tonne
TI	trypsin inhibitor
UAA	utilized agricultural area
USDA	United States Department of Agriculture
US\$	US dollar
WC	white clover
WFPS	water-filled pore space
WIEWS	World Information and Early Warning System
WTO	World Trade Organization

Glossary

Acidification: a process in ecosystems that lowers the pH of soil and water in particular. It is caused by acids and compounds that can be converted into acids. In life cycle assessments, **acidification potential** arises especially from combustion processes, transport and from some nitrogen conversions in the soil.

Biological nitrogen fixation (BNF): the process by which a bacterium, usually in symbiosis with a plant, converts inert nitrogen from the atmosphere into a reactive form, usually ammonium. All agricultural legumes support BNF and they are the only crops that do so.

Blair House Agreement: an agreement made between the USA and the European Union in 1992 as part of the negotiations in the General Agreement on Tariffs and Trade (now the World Trade Organization (WTO)). It aimed to reduce subsidies to exporters and domestic producers, in particular restricting the area of oilseeds supported in Europe to 5.5 million ha.

Break crop: a crop species that differs biologically from the main crops grown. In cereal-based cropping systems, protein, tuber and oilseed crops are break crops.

Common Agricultural Policy (CAP): the agricultural policy of the European Union implements a system of agricultural subsidies and other programmes. It was introduced in 1962 and has undergone several changes since then to reduce the cost and to consider rural development in its aims.

Decoupling: separation of farm payments from production activities. This was a key part of the 2003 reform of the CAP, which packaged all farm payments related to production into a single farm payment under the Single Payment Scheme. These payments were progressively '*decoupled*' from production activities. Payments are now conditional on '*cross-compliance*'.

Diversification measure: one of the '*greening measures*' within the CAP reform proposed by the European Commission. The original proposal is that in most cases, one crop species should not account for more than 70% of the cropped area of a farm, and that at least three crop species should be grown, with none less

than 5%. There is a threshold for the area of arable land on the farm that triggers this requirement.

Ecological focus areas (EFAs): areas of agricultural land (excluding permanent grassland) dedicated to enhancing biodiversity, and one of the ‘*greening measures*’ within the CAP reform proposed by the European Commission (EC). The EC proposed that farmers manage at least 7% of their ‘eligible hectares’ as EFAs as defined in Article 25(2) of the proposal. This means management as fallow land, terraces, landscape features, buffer strips and afforestation. Eligible areas are those that are used for agricultural activity or, where the area is also used for non-agricultural activities, predominantly used for agricultural activities.

Forage legumes: legumes generally fed as a whole plant, including those that are grazed directly by the animal and those that are harvested and fed (green, as silage, or as hay).

Grain legumes: those generally used for their seeds (known as pulses in some countries) for either food or feed.

Greening measures: part of the European Commission’s (EC) proposals published on 12 October 2011 setting out that 30% of direct farm payments be made in return for improvements to the environment and protection of natural resources, additional to those under cross-compliance. The EC hopes to combine viable and diverse food production with improvements to soil, air, water and climate protection. Three measures were proposed: (i) *ecological focus areas*; (ii) *diversification*; and (iii) the preservation of permanent grassland.

Gross margin: revenues (including or excluding subsidies) minus variable costs (excluding fixed and labour costs). It is often the key determinant of the attractiveness of legumes to farmers, indicating the profitability relative to other possible cropping options.

Ley: temporary grassland which is rotated with arable crops.

Monogastric animals: animals having a stomach with only a single compartment, including pigs and poultry. These animals have more specific protein requirements than *ruminants*.

NUTS region: Nomenclature of Units for Territorial Statistics (NUTS), geocode standard by the European Union for referencing the subdivisions of countries for statistical purposes. The NUTS regions are based on the existing national administrative subdivisions and are subdivided into four levels of hierarchy: NUTS 0 are the national states, and NUTS 1–3 are subdivisions into large, medium and small regions, respectively.

Organic: Chemists and biologists use the term ‘organic’ when discussing the chemistry of carbon-based molecules. Thus ‘organic nitrogen’ is nitrogen bound to carbon in such compounds as amino acids and proteins. The opposite is ‘mineral’ and hence ‘mineral nitrogen’ is nitrate, nitrite or ammonium. Decaying biological material in the soil is termed ‘organic matter’. The term ‘soil organic carbon’ is used to distinguish the carbon in organic matter from that in carbonate minerals such as calcium carbonate (chalk).

Organic agriculture: a production management system that aims to promote and enhance agroecosystem health, including biodiversity, biological cycles, and soil biological activity, by using agronomic, biological, and mechanical methods instead of synthetic materials.

Pillar 1: support in the CAP since 2000 that covers all production-related payments such as the direct payments to farmers (as they were known at the time) and market support. Pillar 1 now accounts for about 75% of EU CAP expenditure.

Pillar 2: all CAP payments related to rural development (environmental and social benefits, including the agri-environment schemes and support for young farmers). Pillar 2 accounts for about 25% of CAP expenditure. Pillar 2 payments are co-funded by national governments. Thus shifting from Pillar 1 to 2 can result in a net increase in funding going to rural areas, but a net decrease in funds going directly to farmers.

Pre-crop: the crop grown before the crop in question.

Pre-crop effect: the impact that the preceding crop has on the crop in question.

Protein crop: a legal EU-term including only *pea*, *faba bean* and *lupins*, and used when relating to policies on protein crops.

Ruminant animals: cattle, sheep, goats, deer, antelope and camels. Ruminants have a stomach of four compartments, the first of which is the rumen. They can efficiently digest cellulose, which is the main constituent of forage such as grass.

Single Payment Scheme (SPS): the EU's main agricultural subsidy scheme within the CAP. Farmers receiving payments from the SPS have to satisfy cross-compliance requirements, including farmers' obligations to keep land in good agricultural and environmental condition.

World Trade Organization (WTO): an international organization that establishes global rules of trade between nations. Its main function is to ensure that trade flows as smoothly, predictably and freely as possible. WTO requirements constrain various aspects of the reform of the CAP. *Amber*, *blue*, *green* and *red box measures* refer to WTO conditions.

1

Introduction – Perspectives on Legume Production and Use in European Agriculture

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Abstract

Grain legumes currently cover less than 2% of European arable area, and estimates of forage legume coverage are little greater. Imported legume protein, however, is an important livestock feed additive. This chapter introduces the varied roles of legumes in cropping systems and in food and feed value chains.

Introduction: Importance of Legumes in European Union (EU) Agriculture

Grain and forage legumes play an important role in European agriculture by providing protein-rich food and feed. However, Europe currently depends on importing large quantities of high-protein crop produce (15 million t of soybean and 25 million t of soy meal in 2013 (Eurostat, 2016)) mainly from South America to meet demand for feed for pigs and poultry. This accounted for about 12% of the worldwide production of soybean in 2013/14, and 15 million ha of arable land outside the EU (Westhoek *et al.*, 2011). In 2013, grain legumes were produced on 1.8 million ha of land in Europe (1.6% of the arable area) compared with 5.8 million ha in 1961 (4.7%). On average over the 1961–2011 period, Europe imported 63% of its domestic supply of grain legumes (Cernay *et al.*, 2015, based on FAOSTAT, 2015). Forage is produced on permanent grasslands (pastures), on temporary grassland rotated with arable crops also known as leys, and by dedicated forage legume crops such as lucerne (alfalfa). The area of pasture containing forage legumes, and the proportion of legume in the pasture, is not recorded in all EU countries, making it difficult to estimate their overall contribution. However, estimates from CAPRI, the Common Agricultural Policy Regional Impact modelling

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system (<http://www.capri-model.org/dokuwiki/doku.php> accessed 30 September 2016), suggest that forage legumes play a minor role, covering an average of 3–10% in grassland mixtures in each country (Baddeley *et al.*, 2013), while Eurostat showed pure stands of lucerne and clover on 2.1 million ha in 2009.

The per capita consumption of livestock products continues to increase worldwide (Lassaletta *et al.*, 2014). In Europe, there has been a fourfold increase in poultry meat consumption over the last 50 years, with pig meat consumption increasing by 80% over the same period (Westhoek *et al.*, 2011). The increased consumption of products from monogastric animals has driven changes in the use of crop land and crop products to supply the demand for livestock feed (Pelletier and Tyedmers, 2010) and the increased availability of inexpensive feed has allowed the monogastric sector to grow. This intensification of agriculture has resulted in a shift from pasture-based systems to indoor rearing, influencing the amount of concentrate feed used in livestock production (Hasha, 2002). In Europe, crises in farming such as concerns over animal proteins in livestock diets in the 1990s (bovine spongiform encephalopathy (BSE)) have also changed livestock diets, contributing to the further increase in the use of soybean in livestock diets (Vicenti *et al.*, 2009).

Increasing home-grown production of legumes is attractive because it contributes to the sustainable development of European agriculture by a variety of mechanisms, including reduced dependence on fossil fuels in agriculture, reduced greenhouse gas (GHG) emissions, increased crop diversity in cropping systems, increases in above and below ground biodiversity, improved soil fertility, increased carbon storage, and reconnection of crop and livestock production. Perhaps the most distinctive and valuable feature of legumes is their capacity for biological nitrogen fixation (BNF) in symbiosis with bacteria in the *Rhizobiaceae*. This book explores some agronomic and environmental aspects of the current production of forage and grain legumes in Europe. We exclude leguminous trees such as carob because of their minor economic role, although they have value as feed, food and fuel resources.

Producing Legumes

Grain production systems

Grain legumes are produced in a variety of ways across Europe, including as dry grain, green forage, arable silage and green manure, with the choice often depending on climatic and edaphic conditions as well as intended end-use. Several species are grown in Europe, some with both spring-sown and autumn-sown variants. The main species are pea (*Pisum sativum* L.), lupins (*Lupinus* spp.), faba bean (*Vicia faba* L.), chickpea (*Cicer arietinum* L.), lentil (*Lens culinaris* Medik.), common bean (*Phaseolus vulgaris* L.) and soybean (*Glycine max* (L.) Merr.). Although soybean is officially classified by the Food and Agriculture Organization of the United Nations (FAO) as an oilseed crop rather than a protein crop, it has a similar function in cropping systems to the other grain legumes and is the reference protein crop, so we include it here. Grain legumes are most commonly produced as sole

crops, although there is currently great interest in intercropping (Malézieux *et al.*, 2009). Cereal/legume intercrops can be grown for grain or silage, the latter as a way of boosting the forage protein content of livestock diets (Anil *et al.*, 1998) mainly under wetter conditions in northern and western Europe, and in some situations have a higher and more stable gross margin than the mean of the sole crops (Bedoussac *et al.*, 2015).

Forage production systems

Forage is produced on permanent grasslands (pastures), on temporary grassland rotated with arable crops also known as leys, and by dedicated forage legume crops such as lucerne (*Medicago sativa* L.). Although forage legumes are grown in an estimated 2.1 million ha as pure stands (Eurostat data for 2009), they are more generally grown in mixtures with grasses, other legumes and forbs. They are attractive because: (i) they allow reduction or elimination of nitrogen (N) fertilizer use; and (ii) they benefit the farming system by supplying N to following crops, and improving soil structure and biodiversity. Grass–legume mixtures provide significant agronomic benefits in terms of yield, agronomic quality, low input costs, and feed quality as compared with pure grass and (sometimes) silage maize (Peyraud *et al.*, 2009). Disadvantages include slow growth in spring (Peyraud *et al.*, 2009), less persistence than grass under grazing, risk of livestock bloat and some difficulties in conservation as hay or silage (Phelan *et al.*, 2015). They are also used in some medium intensity systems to reduce the need for fertilizer N (e.g. organic grasslands). The use of fertilizer reduces clover content of mixtures below 50% (Carlsson and Huss-Danell, 2003) and the combination of high fertilizer use and stocking rates practically eliminates the legume component (clover) and its impact (O'Mara, 2008).

Red clover (*Trifolium pratense* L.) leys generally last 2–3 years, whereas white clover (*Trifolium repens* L.) stands can last 15 years or more (Humphreys *et al.*, 2008; Stoddard *et al.*, 2009). White clover is the subject of Chapter 9, this volume, and red clover of Chapter 10, where their management is discussed in detail.

Nutrition – Humans and Livestock

Grain legumes are important in the human diet in providing protein, essential amino acids and nutrients through direct consumption and indirectly through meat, fish, milk and eggs. Current nutritional guides such as *The Eatwell Guide* in the UK (Public Health England, 2016) and the Finnish National Nutrition Council (VRN, 2014) suggest decreased consumption of animal protein and increased use of vegetable protein, particularly from food legumes. Grain legume seeds contain protein, energy in the form of starch or oil, dietary fibre, micro- and macronutrients, vitamins and numerous bioactive phytochemicals (Strohle *et al.*, 2006), such as flavonoids and other antioxidants (Scalbert *et al.*, 2005). They provide dietary iron, zinc and calcium, all of which are important for humans and monogastric animals, but the availability of these nutrients is reduced by chelation

to inositol hexakisphosphate (phytate). There is increasing interest in the use of preparation procedures such as germination and fermentation to enhance both macro and trace element availability (Humer and Schedle, 2016). The protein content of grain legume species ranges from 20% in common bean and lentil to 40% in soybean and yellow lupin (see Chapter 5, this volume). This compares with 7–17% in cereals and 17–26% in rapeseed (Day, 2013). There are significant positive effects on human health when animal proteins are replaced by plant protein including lowering cholesterol (Harland and Haffner, 2008), controlling hypertension (Harland and Haffner, 2008) and improving cardiovascular health (Sirtori *et al.*, 2009). Eating soybean and lupin can decrease cholesterol in humans (Sirtori *et al.*, 2012), and grain legumes may also be useful in the diet of diabetics (Bertoglio *et al.*, 2011) and in maintaining a healthy weight (McCrorry *et al.*, 2010). A role in prevention of some cancers has also been suggested (Campos-Vega *et al.*, 2010). There is a large body of research on the health benefits of pulses (the starchy grain legumes), including a special issue of the *British Journal of Nutrition* in 2012 (volume 108, Supplement S1).

In addition to their high protein content, forage legumes have the advantage of high voluntary intake and animal production when feed supply is non-limiting (Phelan *et al.*, 2015). A literature review (Steinshamn, 2010) showed that red clover and white clover increased dry matter intake by 1.2 kg and 1.3 kg, respectively, relative to grass-based diets and that milk yield was 1.5 kg/day and 2.2 kg/day higher, respectively. Condensed tannins present in forage legumes can benefit ruminant animal health, by reducing the risk of bloat and the parasitic worm burden (Waghorn, 2008) as well as potentially reducing GHG emissions (Beauchemin *et al.*, 2008; Azunhwi *et al.*, 2013). The consumer can also benefit from the impacts of bioactive compounds present in legumes such as condensed tannins and polyphenols through both improved meat flavour (Schreurs *et al.*, 2007) and increased levels of beneficial fatty acids (Girard *et al.*, 2015).

Legumes have the potential to replace part or all of the fish meal in the diets of farmed fish and the potential of a range of plant-based protein sources was recently reviewed by Ayadi *et al.* (2012). Grain legumes are a suitable feed for herbivorous fish such as carp (*Cyprinus carpio*), but a variety of legume-based extrudates can substitute for the fish meal normally used for many farmed carnivorous fish and crustaceans (Trushenski *et al.*, 2006). Soybean, particularly in high doses, can reduce growth rate due, at least in part, to antinutritional components (Kroghdahl *et al.*, 2010), but work is underway to breed new lines of soybean specifically for aquaculture (Herman and Schmidt, 2016). Compounded fish feeds contained a mean of 25% soybean meal in 2008, representing 4.5% of world soybean meal production in that year, and a trend was detected for increased use of other pulse and cereal proteins (Tacon *et al.*, 2011). There are numerous studies in the literature focusing on determining the best grain legume protein, and its optimal proportion in the diet, for different fish. For example, rainbow trout grew well on up to 30% narrow-leaved lupin meal (Glencross *et al.*, 2008). Faba bean or pea flour can replace some of the wheat or other cereal starch in the formulation of feed pellets under heat extrusion. Blending of different protein sources into a mixture is also common, as it balances the amino acid composition and dilutes the

antinutritional effects of individual components (Gomes *et al.*, 1995). These aspects were reviewed in a Legume Futures report on novel feed and non-food uses of legumes (Stoddard, 2013).

The FAO (2004) estimated that soybean meal accounted for 75% of the high-protein raw materials used in compounded livestock feeds. The amount of soy required per kilogram of product ranges from 11 g/kg for raw milk through 330 g/kg for eggs to 600 g/kg for poultry meat (Hoste and Bolhuis, 2010).

Legumes protect themselves from oxidative stresses and herbivores with a range of secondary compounds, including alkaloids, saponins and isoflavonoids that often have so-called antinutritional effects. The presence of these antinutritional factors substantially limits the use of legumes in monogastric diets, sometimes through reducing nutrient digestibility and absorption (Gatel, 1994), sometimes affecting feed intake and nutrient digestibilities, and sometimes, such as vicine-convicine to chickens, toxicity (e.g. Huisman and Jansman, 1991). These antinutritional factors include non-starch polysaccharides (NSP), tannins, alkaloids, pyrimidine glycosides, lectins and trypsin inhibitors (TIs), depending on the species (see Chapter 5, this volume). Soybean meal (SBM) is the main protein supplement in pig feed (Crépon 2006; Jezierny *et al.*, 2010) due to its high crude protein (CP) content (44%) and useful amino acid profile, but its powerful TIs require denaturing. The rising costs of soybean meal and the environmental controversy over soybean imports has given rise to increased interest in the use of alternative home-produced legumes. Other grain legumes contain considerably less protein and quite different amino acid profiles, with methionine and tryptophan being the usual limiting amino acids. White *et al.* (2015) recently demonstrated the viability of alternative grower and finisher pig diets formulated from pea and faba bean. Pea, low-vicine faba bean and lupins all work as partial substitutes for soybean in broiler diets, with pea generally performing best (Diaz *et al.*, 2006; Palander *et al.*, 2006). These alternatives to soybean have also been shown to be acceptable in egg production (Laudadio and Tufarelli, 2010). Soybean in ruminant rations can also be partially replaced by pea, faba bean and lupins (Vander Pol *et al.*, 2008; Volpelli *et al.*, 2010; Dawson, 2012). This can potentially affect both yield and product quality (Renna *et al.*, 2012).

Some secondary compounds have medicinal uses. Two well-known drugs derived from products of forage legumes are the antithrombotic warfarin, which comes from sweet clover's coumarin, and the antidiabetic metformin, derived from sainfoin's guanidine. In some cases, analysis has not proceeded beyond a crude aqueous or solvent extract, but in many cases the specific active compound has been identified and tested. Cornara *et al.* (2015) recently reviewed temperate forage legumes as a resource for nutraceuticals and pharmaceuticals.

Non-food Uses of Legumes

During the Legume Futures project, non-food uses of legumes were surveyed and catalogued, with a focus on bioenergy and phytoremediation (Stoddard, 2013).

Bioenergy

Legumes have a potential role in bioenergy cropping as they reduce reliance on synthetic fertilizer and thus fossil fuel energy, with associated reductions in GHG emissions.

First-generation biofuels are made using simple technologies in order to replace fossil fuels. Legume starch can be converted to bioethanol in the same way as cereal starch, but since starchy legumes generally yield much less than cereals and their starch content is lower, it is highly unlikely that this will ever be economic or sustainable. An early life-cycle analysis of bioenergy production showed that the BNF capacity of soybean gave it a significant advantage over other oilseeds (Hill *et al.*, 2006), but, given the value of soy for food and feed, it is unlikely to ever be grown primarily for energy.

Intercropping bioenergy grasses with legumes can reduce N fertilizer requirements. In North America, switchgrass (*Panicum virgatum* L.) yield was not significantly affected by selected legume intercrops, particularly lucerne where soil fertility was low, but N fertilization was greatly reduced or eliminated (Wang *et al.*, 2010; Butler *et al.*, 2013). Comparable datasets from Europe are scarce, but at high latitudes, the N fertilization requirement of reed canary grass (*Phalaris arundinacea* L.) can be reduced by mixed cropping with *Galega orientalis* Lam. with a mild reduction in yield (Epie *et al.*, 2015). Use of BNF in this way generally reduces nitrous oxide (N₂O) emission, contributing to GHG mitigation.

Biorefining offers another way of combining feed and bioenergy production (Jensen *et al.*, 2012). Leaves or leaf protein of lucerne, clover–grass or clover–cereal mixtures can be used for livestock feed and the lignified stems as feedstock for either biofuel or biodegradable plastics (Thomsen and Hauggaard-Nielsen, 2008; González-García *et al.*, 2010; Kamm *et al.*, 2010).

Phytoremediation

Phytoremediation, or plant-based bioremediation, is a way of using contaminated ground for the production of bioenergy or other industrial products, when growing food or feed is considered inappropriate.

Petroleum oil raises the carbon-to-nitrogen ratio of soil, so the BNF capacity of legumes is a valuable attribute. It also generally includes polycyclic aromatic hydrocarbons (PAHs) that are very toxic and durable, but poorly mobile. Plants have little direct effect on the degradation of petroleum residues; rather, their associated rhizosphere microbes are responsible. Thus in pot experiments, *G. orientalis* inoculated with *Rhizobium galegae* promoted oil degradation (Jussila *et al.*, 2006; Kaksonen *et al.*, 2006), but in field experiments there was little difference between galega, brome grass, their mixture, and bare fallow on the rate of oil degradation (Yan *et al.*, 2015).

Sunn hemp (*Crotalaria juncea* L.) produces long fibres that can be used in similar ways to hemp or jute (Ingle and Doke, 2006), along with pyrrolizidine alkaloids that can bioremediate nematode-infested soils, making it a potentially valuable multi-purpose crop. Field experiments in many warm climates

have demonstrated the resistance of *Crotalaria* species to root-knot, root-lesion and other nematodes that parasitize crop plants. Laboratory studies have shown that the alkaloids from sunn hemp species paralyse some nematodes and arrest the development of others (Subramanian and Vadivelu, 1990; Jourand *et al.*, 2004; Curto *et al.*, 2015). Sunn hemp can be used as a green manure to control nematodes in field (Curto *et al.*, 2015) and greenhouse (Lajudie *et al.*, in preparation, reported by Stoddard, 2013) production of vegetables.

Legumes in Crop Rotations

Grain legumes are usually handled as components of crop rotations or sequences rather than as continuous monocultures, because they are just as susceptible to the build-up of soil-borne pathogens and pests as any other arable species. In order to optimize management of pests, weeds and diseases, and to exploit nutrient availability through the soil profile, crop rotations or sequences should incorporate species with different life cycles, growth habits, root architectures and pest spectra (Cook, 2013; Garrison *et al.*, 2014; Reckling *et al.*, 2016a). Rotations are widely understood to improve soil structure, permeability, microbial activity, water storage capacity, organic matter content and resistance to erosion, thus increasing crop yields and sustainability of production systems (Bullock, 1992; Karlen *et al.*, 1994). Both BNF (Knight, 2012) and soil microbial function (Lupwayi *et al.*, 2012) are affected by the frequency of grain legume production. It is usually necessary to inoculate the legume with an appropriate strain of *Rhizobium* if it is to be sown where it or a related species has not been produced within the previous 5 years, and this inoculation often results in improved legume yields and contributions to soil fertility (Denton *et al.*, 2013). Low soil pH reduces the survival time of rhizobia when no legume host is present (Carter *et al.*, 1995).

A legume influences following crops through a set of 'break-crop', 'nitrogen' and 'legume-specific' effects (Chalk, 1998; Peoples *et al.*, 2009). The break-crop effect occurs when a cropping sequence lacking diversity, such as the continuous production of small-grain cereals (wheat and barley) typical of most of Europe, is 'broken' by a broadleaved crop or a ley (Robson *et al.*, 2002). The most important part of the effect is the reduction in soil-borne diseases of cereals (Kirkegaard *et al.*, 2008), while other components include the removal of hosts of other pests and the opportunity to use alternative methods and agrochemicals for pest, pathogen and weed reduction (Prew and Dyke, 1979; Stevenson and van Kessel, 1997) and improvements in soil structure (Chan and Heenan, 1996). The nitrogen effect is the release of biologically fixed N from legume residues, the rate of which is affected by their relatively low C:N ratio, and the impact on the following crop is clearer in sandy than loamy soils (Jensen *et al.*, 2004). The key part of the legume-specific effect is the enhanced growth of plant growth-promoting bacteria (Lugtenberg and Kamilova, 2009), particularly hydrogen-fixing bacteria (Maimaiti *et al.*, 2007), contributing to the improved growth of the following crops such as broccoli after narrow-leafed lupin (Thorup-Kristensen, 1993). The taproot architecture and coarse lateral roots of grain legumes, in contrast to the fine network of cereal roots, assist water infiltration and form channels followed

by the roots of the subsequent crop, but may also affect leaching (Dunbabin *et al.*, 2003; Neumann *et al.*, 2011). The N content of the legume residues influences the potential for nitrate leaching and N₂O emissions (Pappa *et al.*, 2011), increasing the value of an N-retaining cover crop, particularly when the following crop is spring sown, leaving a winter fallow (Tuulos *et al.*, 2014). When used as a cover crop, a grain legume can supply N to the following crop while protecting the bare soil, and mixtures of legumes with other crops further reduce leaching potential (Tosti *et al.*, 2014), with vetches being the most cost-effective (Büchi *et al.*, 2015). N and phosphorus losses, and ways to limit them, are covered in greater detail in Chapter 3, this volume. The impacts of legumes on biodiversity are reviewed by Everwand *et al.* (Chapter 4) in this volume.

Current Perspectives on Legume Production

Within the Legume Futures project we carried out a set of 'case studies', in the sociological sense of the term, in which experts were asked about their knowledge and opinions on various legume-related issues. In [Table 1.1](#), we summarize the opportunities and the challenges for the four main agroclimatic regions (Metzger *et al.*, 2005) as identified by project partners and their local colleagues. Although there were clear regional differences in species grown and agronomic constraints, there were common features as well. A need for economic and environmental evaluation of legume impacts was widely seen. Novel food uses and other innovations could increase demand, which it was hoped would lead to increased profitability. All regions needed better cultivars with higher yield, greater stress resistance and improved quality.

We drew on a network of field research sites across a wide range of agricultural regions of Europe, where legumes had been used in cropping system studies. The network was carefully selected to cover a wide variety of agro-economic and pedo-climatic zones across Europe, and also covers a range of different uses. By utilizing existing experiments the project aimed to achieve a broad overview of contrasting farming systems with the project resources used to derive additional benefits from their networking. The coverage extended from Jokioinen, Finland in the north (60.81°N 23.49°E) to Fundulea, Romania in the east (44.46°N 26.51°E), Córdoba, Spain in the south (37.46°N 4.31°W) and Solohead, Ireland in the west (52.51°N 8.21°W). Each field site tested certain environmental impacts, and in some cases provided many decades of data ([Table 1.2](#)). Five of these locations were used as test sites for examining potential crop rotations and their environmental impacts: (i) the Leibniz Centre for Agricultural Landscape Research (ZALF) Brandenburg; (ii) the Swedish University of Agricultural Sciences (SLU) Skåne; (iii) Scotland's Rural College (SRUC) Edinburgh; (iv) Fundulea; and (v) Reggio Calabria.

It became clear during the project that the assessment of a legume crop in isolation was not enough. The environmental impacts of legume crops are felt over more than one season and beyond the farm gate, so their economic impacts extend in comparable ways. For these reasons, a multi-criteria assessment framework was developed on two sites, integrating leaching potential and GHG emission

Table 1.1. Expert opinions from the panel of Legume Futures specialists on the attributes and potentials of grain legumes in the four mega-climatic regions of Europe.

	Atlantic	Continental–Pannonian	Mediterranean	Boreal–Nemoral
Countries contributing	UK and Ireland	Germany, Romania	Italy, Greece, Spain	Denmark, Finland, Sweden
Main forage legumes	White clover	Lucerne, clovers, serradella	Irrigated lucerne	Red clover
Main grain legumes	Pea, faba bean	Pea, faba bean, soybean, lupin, lentil	Wide range, including chickpea	Pea, faba bean
Major agronomic constraints	Weed control in grain legumes	Yield stability in grain legumes, soil-borne and other diseases, weed infestation, drought	Weed control, yield stability	Disease (e.g. aphanomyces, chocolate spot, grey mould), competitiveness against weeds (especially in organic systems), yield stability
Supply chain constraints	Feed quality, lack of processing facilities	Varying prices and qualities of legume fodder compounds results in low market demands	No answer	Markets needed to encourage farmers to grow grain legumes, companies have difficulty handling small volumes of variable quality
Farmer knowledge needs (mix of knowledge exchange and research needs)	Agronomic info, value of legumes in rotations, consistency of performance (clover), quantity of N fixed, economic and environmental information	Lack of knowledge about water use, economic and environmental information	Green manures and intercropping, economic and environmental information, lack of knowledge among young farmers	Perception that it takes too long to provide N via legumes
Policy needs	Economic and environmental evaluation	Economic and environmental evaluation	Economic and environmental evaluation	No answer

Continued

Table 1.1. Continued.

	Atlantic	Continental–Pannonian	Mediterranean	Boreal–Nemoral
Other needs	Consumer education	No answer	Better extension service	No answer
Growth areas/ opportunities	Beans for feed (fish and monogastrics), increased use of white clover in pastures to reduce fertilizer N use, legumes for perennial systems (e.g. agroforestry)	Demand for GM-free ^a food, functional foods and locally produced food/feed	Legumes for food, green manures for soil fertility, intercropping for forage and grain, use of intercrop residues for biofuel production, engagement of seed companies in promotion	Novel food uses, lucerne for restoring compacted soils, growth in organic production will drive legume production
Breeding demand	Early maturing winter beans, cultivars compatible with undersowing or intercropping with cereals	Winter hardiness, disease resistance, low contents of antinutritional compounds, peas with stiffer straw, autumn-sown cultivars of grain legumes	Adapted cultivars for winter sowing, many landraces used in some countries, cultivars for intercropping	Earlier maturity especially in beans, better feed quality, disease resistance, processing to improve feed quality

^aGM, Genetically modified.

Table 1.2. Field experiments used in the Legume Futures project.

Country	Institution ^a	Primary purpose of the field experiment ^b	Environmental impacts investigated
Denmark	Aarhus University	Organic/conventional cropping comparison including dairy, mixed cropping, rotations, assessment of leaching, GHG and NH ₃ emissions (three sites)	N cycling
Finland	University of Helsinki	Rotations, crop diversity, intercropping	Bioremediation, multifunctionality
Finland	LUKE	Organic/conventional cropping comparison with and without livestock, green manure, leaching	Multifunctionality
France	CIRAD	Green manure in greenhouse vegetable production	Biological control of nematodes
Germany	ZALF	Organic dairy farming	Weed reduction, nutrient dynamics
Germany	Von Thünen Institute	Mixed organic cropping, rotations, whole-crop silage, leaching assessment	N cycling
Greece	Agricultural University of Athens	Organic/conventional cropping comparison	Salinity management
Ireland	Teagasc and Trinity College Dublin	Mineral N vs BNF, N flow, life cycle assessment, leaching	Biodiversity, disease cycles, N cycling
Italy	Università Mediterranea di Reggio Calabria	Legume–cereal intercropping	N cycling, biodiversity, multifunctionality
Poland	IUNG-PIB	Organic/conventional ('integrated') cropping comparison, crop rotation	N cycling
Romania	Agricultural University of Romania at Fundulea	Organic cropping; cultivars for organic systems	N cycling, biodiversity
Spain	University of Córdoba	Rotations, tillage; broomrape control	N cycling, disease cycles, C sequestration
Sweden	SLU	Rotations; non-dairy systems (three sites)	Disease cycles, N cycling
UK	SRUC	1: Organic rotation; stocked and stockless systems, GHG exchanges; 2: Synthetic nitrogen sources; GHG exchange	Nutrient dynamics
UK	James Hutton Institute	Stockless, arable rotations, conventional and alternative strategies for nutrient supply	N cycling, biodiversity, disease cycles, multifunctionality

^aCIRAD, Agricultural Research Centre for International Development; IUNG-PIB, Institute of Soil Science and Plant Cultivation; LUKE, Natural Resources Institute; SLU, Swedish University of Agricultural Sciences; SRUC, Scotland's Rural College; ZALF, Leibniz Centre for Agricultural Landscape Research.

^bBNF, Biological nitrogen fixation; C, carbon; GHG, greenhouse gas; N, nitrogen; NH₃, ammonia.

risk along with the gross margins of crop production including pre-crop effects in a modified rotation generator (Reckling *et al.*, 2016a) and extended to five sites (Reckling *et al.*, 2016b). On average, N₂O emission was reduced in legume-supported systems by 18% (arable) and 33% (forage), while nitrate leaching potential was reduced by 24% and 38%, respectively). Gross margins were improved by legumes in all three forage test cases, but in only two of the five arable test cases (Reckling *et al.*, 2016b). Novel rotations were generated that provided higher potential gross margins than the current general practice. Related economic aspects of using legumes in European agricultural systems are covered by Preissel *et al.* (Chapter 13, this volume) and the attendant policy issues by Kuhlman *et al.* (Chapter 14, this volume) in this volume.

Conclusion

Grain and forage legumes have considerable potential in European cropping systems. When used wisely and produced with appropriate attention to their requirements, they can improve the environmental impact of agriculture and farm incomes. This book presents chapters on the complete legume chain, from the production of forage and grain species, to their impacts on the environment, the economy and the human diet. The perspective is European throughout, with overseas data included where appropriate.

References

- Anil, L., Park, J., Phipps, R.H. and Miller, F.A. (1998) Temperate intercropping of cereals for forage: a review of the potential for growth and utilization with particular reference to the UK. *Grass and Forage Science* 53, 301–307.
- Ayadi, F.Y., Rosentrater, K.A. and Muthukumarappan, K. (2012) Alternative protein sources for aquaculture feeds. *Journal of Aquaculture Feed Science and Nutrition* 4, 1–26.
- Azuhnwi, B.N., Hertzberg, H., Arrigo, Y., Gutzwiller, A., Hess, H.D., Mueller-Harvey, I., Torgerson, P.R., Kreuzer, M. and Dohme-Meier, F. (2013) Investigation of sainfoin (*Onobrychis viciifolia*) cultivar differences on nitrogen balance and fecal egg count in artificially infected lambs. *Journal of Animal Science* 91, 2343–2354.
- Baddeley, J.A., Jones, S., Topp, C.F.E., Watson, C.A., Helming, J. and Stoddard, F.L. (2013) Biological nitrogen fixation (BNF) by legume crops in Europe. Legume Futures Report 1.5. Available at: www.legumefutures.de (accessed 30 March 2016).
- Beauchemin, K.A., Kreuzer, M., O'Mara, F. and McAllister, T.A. (2008) Nutritional management for enteric methane abatement: a review. *Australian Journal of Experimental Agriculture* 48, 21–27.
- Bedoussac, L., Journet, E.-P., Hauggaard-Nielsen, H., Naudin, C., Corre-Hellou, G., Jensen, E.S., Prieur, L. and Justes, E. (2015) Ecological principles underlying the increase of productivity achieved by cereal–grain legume intercrops in organic farming. A review. *Agronomy for Sustainable Development* 35, 911.
- Bertoglio, J.C., Calvo, M.A., Hancke, J.L., Burgos, R.A., Riva, A., Morazzoni, P., Ponzone, C., Magni, C. and Duranti, M. (2011) Hypoglycemic effect of lupin seed γ -conglutin in experimental animals and healthy human subjects. *Fitoterapia* 82, 933–938.

- Büchi, L., Gebhard, C.A., Liebisch, F., Sinaj, S., Ramseier, H. and Charles, R. (2015) Accumulation of biologically fixed nitrogen by legumes cultivated as cover crops in Switzerland. *Plant and Soil* 393, 163–175.
- Bullock, D.G. (1992) Crop rotation. *Critical Reviews in Plant Science* 11, 309–326.
- Butler, T.J., Muir, J.P., Huo, C. and Guretzky, J.A. (2013) Switchgrass biomass and nitrogen yield with overseeded cool-season forages in the southern Great Plains. *Bioenergy Research* 6, 44–52.
- Campos-Vega, R., Loarca-Pina, G. and Oomah, B.D. (2010) Minor components of pulses and their potential impact on human health. *Food Research International* 43, 461–482.
- Carlsson, G. and Huss-Danell, K. (2003) Nitrogen fixation in perennial forage legumes in the field. *Plant and Soil* 253, 353–372.
- Carter, J.M., Tieman, J.S. and Gibson, A.H. (1995) Competitiveness and persistence of strains of rhizobia for faba bean in acid and alkaline soils. *Soil Biology and Biochemistry* 27, 617–623.
- Cernay, C., Ben-Ari, T., Pelzer, E., Meynard, J.-M. and Makowski, D. (2015) Estimating variability in grain legume yields across Europe and the Americas. *Scientific Reports* 5, 11171.
- Chalk, P.M. (1998) Dynamics of biologically fixed N in legume–cereal rotations: a review. *Australian Journal of Agricultural Research* 49, 303–316.
- Chan, K.Y. and Heenan, D.P. (1996) The influence of crop rotation on soil structure and soil physical properties under conventional tillage. *Soil and Tillage Research* 37, 113–125.
- Cook, D., Grum, D.S., Gardner, D.R., Welch, K.D. and Pfister, J.A. (2013) Influence of endophyte genotype on swainsonine concentrations in *Oxytropis sericea*. *Toxicon* 61, 105–111.
- Cornara, L., Xiao, J.B. and Burlando, B. (2015) Therapeutic potential of temperate forage legumes: a review. *Critical Reviews in Food Science and Nutrition* 56, S149–S161.
- Crépon, K. (2006) Nutritional value of legumes (pea and faba bean) and economics of their use. In: Garnsworthy, P.C. and Wiseman, J. (eds) *Recent Advances in Animal Nutrition*. Nottingham University Press, Nottingham, UK, pp. 331–366.
- Curto, G., Dallavalle, E., Santi, R., Casadei, N., D'Avino, L. and Lazzeri, L. (2015) The potential of *Crotalaria juncea* L. as a summer green manure crop in comparison to *Brassicaceae* catch crops for management of *Meloidogyne incognita* in the Mediterranean area. *European Journal of Plant Pathology* 142, 829–841.
- Dawson, L.E.R. (2012) The effect of inclusion of lupins/triticale whole crop silage in the diet of winter finishing beef cattle on their performance and meat quality at two levels of concentrates. *Animal Feed Science and Technology* 171, 75–84.
- Day, L. (2013) Proteins from land plants – potential resources for human nutrition and food security. *Trends in Food Science and Technology* 32, 25–42.
- Denton, M.D., Pearce, D.J. and Peoples, M.B. (2013) Nitrogen contributions from faba bean (*Vicia faba* L.) reliant on soil rhizobia or inoculation. *Plant Soil* 365, 363–374.
- Diaz, D., Morlacchini, M., Masoero, F., Moschini, M., Fusconi, G. and Piva, G. (2006) Pea seeds (*Pisum sativum*), faba beans (*Vicia faba* var. *minor*) and lupin seeds (*Lupinus albus* var. *multitalia*) as protein sources in broiler diets: effect of extrusion on growth performance. *Italian Journal of Animal Science* 5, 43–53.
- Dunbabin, V., Diggle, A. and Rengel, Z. (2003) Is there an optimal root architecture for nitrate capture in leaching environments? *Plant, Cell and Environment* 26, 835–844.
- Epie, K.E., Saikkonen, L., Santanen, A., Jaakkola, S., Mäkelä, P., Simojoki, A. and Stoddard, F.L. (2015) Nitrous oxide emissions from perennial grass–legume intercrop for bioenergy use. *Nutrient Cycling in Agroecosystems* 101, 211–222.
- Eurostat (2016) Eurostat. European Commission, Brussels. Available at: <http://ec.europa.eu/eurostat> (accessed 30 April 2016).
- FAOSTAT (2015) Statistics Database of the Food and Agriculture Organization of the United Nations. Food and Agriculture Organization of the United Nations, Rome. Available at: <http://faostat3.fao.org/home/E> (accessed 2 February 2016).

- Food and Agriculture Organization of the United Nations (FAO) (2004) Protein sources for the animal feed industry. In: *Proceedings of An Expert Consultation and Workshop*, Bangkok, 29 April–3 May 2002. FAO, Rome, pp. ix–xxv.
- Garrison, A.J., Miller, A.D., Ryan, M.R., Roxburgh, S.H. and Shea, K. (2014) Stacked crop rotations exploit weed–weed competition for sustainable weed management. *Weed Science* 62, 166–176.
- Gatel, F. (1994) Protein quality of legume seeds for non-ruminant animals: a literature review. *Animal Feed Science and Technology* 45, 317–348.
- Girard, M., Dohme-Meier, F., Silacci, P., Ampuero Kragten, S., Kreuzer, M. and Bee, G. (2015) Forage legumes rich in condensed tannins may increase n-3 fatty acid levels and sensory quality of lamb meat. *Journal of the Science of Food and Agriculture* 96, 1923–1933.
- Glencross, B., Hawkins, W., Evans, D., Rutherford, N., Dods, K., McCafferty, P. and Sipsas, S. (2008) Evaluation of the influence of *Lupinus angustifolius* kernel meal on dietary nutrient and energy utilization efficiency by rainbow trout (*Oncorhynchus mykiss*). *Aquaculture Nutrition* 14, 129–138.
- Gomes, E.F., Rema, P. and Kaushik, S.J. (1995) Replacement of fish meal by plant proteins in the diet of rainbow trout (*Oncorhynchus mykiss*): digestibility and growth performance. *Aquaculture* 130, 177–186.
- González-García, S., Moreira, M.T. and Feijoo, G. (2010) Environmental performance of ligno-cellulosic bioethanol production from alfalfa stems. *Biofuels, Bioproducts and Biorefining* 4, 118–131.
- Harland, J.I. and Haffner, T.A. (2008) Systematic review, meta-analysis and regression of randomised controlled trials reporting an association between an intake of circa 25 g soya protein per day and blood cholesterol. *Atherosclerosis* 200, 13–27.
- Hasha, G. (2002) Livestock feeding and feed imports in the European Union – A decade of change. FDS-0602-01. *Electronic Outlook Report from the Economic Research Service, Economic Research Service (ERS), United States Department of Agriculture (USDA)*, 28 pp. Available at: <http://www.ers.usda.gov/media/1725328/fds060201.pdf> (accessed 30 September 2016).
- Herman, E.M. and Schmidt, M.A. (2016) The potential for engineering enhanced functional-feed soybeans for sustainable aquaculture feed. *Frontiers in Plant Science* 7, 440.
- Hill, J., Nelson, E., Tilman, D., Polasky, S. and Tiffany, D. (2006) Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels. *Proceedings of the National Academy of Sciences of the USA* 103, 11207–11211.
- Hoste, R. and Bolhuis, J. (2010) *Soya Consumption in the Netherlands*. Landbouw-Economisch Instituut (LEI) Report 2010-059. LEI, The Hague, the Netherlands.
- Huisman, J. and Jansman, A.J.M. (1991) Dietary effect and some analytical aspects of antinutritional factors in peas (*Pisum sativum*), common beans (*Phaseolus vulgaris*) and soybeans (*Glycine max* L.) in monogastric farm animals: a literature review. *Nutrition Abstracts and Reviews (Series B)* 60, 901–921.
- Humer, E. and Schedle, K. (2016) Fermentation of food and feed: a technology for efficient utilization of macro and trace elements in monogastrics. *Journal of Trace Elements in Medicine and Biology* 37, 69–77.
- Humphreys, J., O’Connell, K. and Casey, I.A. (2008) Nitrogen flows and balances in four grassland-based systems of dairy production on a clay-loam soil in a moist maritime climate. *Grass and Forage Science* 63, 467–480.
- Ingle, N.P. and Doke, S.S. (2006) Analysis of sunnhemp fibers processed using jute spinning system. *Industrial Crops and Products* 23, 235–243.
- Jensen, C.R., Joernsgaard, B., Andersen, M.N., Christiansen, J.L., Mogensen, V.O., Friis, P. and Petersen, C.T. (2004) The effect of lupins as compared with peas and oats on the yield of the subsequent winter barley crop. *European Journal of Agronomy* 20, 405–418.

- Jensen, E.S., Peoples, M.B., Boddey, R.M., Gresshoff, P.M., Hauggaard-Nielsen, H., Alves, B.J.R. and Morrison, M.J. (2012) Legumes for mitigation of climate change and the provision of feedstock for biofuels and biorefineries. A review. *Agronomy for Sustainable Development* 32, 329–364.
- Jezierny, D., Mosenthin, R. and Bauer, E. (2010) The use of grain legumes as a protein source in pig nutrition: a review. *Animal Feed Science and Technology* 157, 111–128.
- Jourand, P., Rapior, S., Fargette, M. and Mateille, T. (2004) Nematostatic activity of aqueous extracts of West African *Crotalaria* species. *Nematology* 6, 765–771.
- Jussila, M.M., Jurgens, G., Lindström, K. and Suominen, L. (2006) Genetic diversity of culturable bacteria in oil-contaminated rhizosphere of *Galega orientalis*. *Environmental Pollution* 139, 244–257.
- Kaksonen, A.H., Jussila, M.M., Lindström, K. and Suominen, L. (2006) Rhizosphere effect of *Galega orientalis* in oil-contaminated soil. *Soil Biology and Biochemistry* 38, 817–827.
- Kamm, B., Hille, C., Schönicke, P. and Dautzenberg, G. (2010) Green biorefinery demonstration plant in Havelland (Germany). *Biofuels, Bioproducts and Biorefining* 4, 253–262.
- Karlen, D.L., Varvel, G.E., Bullock, D.G. and Cruse, R.M. (1994) Crop rotations for the 21st century. *Advances in Agronomy* 53, 1–45.
- Kirkegaard, J.A., Christen, O., Krupinsky, J. and Layzell, D. (2008) Break crop benefits in temperate wheat production. *Field Crops Research* 107, 185–195.
- Knight, J. D. (2012) Frequency of field pea in rotations impacts biological nitrogen fixation. *Canadian Journal of Plant Science* 92, 1005–1011.
- Kroghdahl, Å., Penn, M.H., Thorsen, J., Refstie, S. and Bakke, A.M. (2010) Important antinutrients in plant feedstuffs for aquaculture: an update on recent findings regarding responses in salmonids. *Aquaculture Research* 41, 333–344.
- Lassaletta, L., Billen, G., Romero, E., Garnier, J. and Aguilera, E. (2014) How changes in diet and trade patterns have shaped the N cycle at the national scale: Spain (1961–2009). *Regional Environmental Change* 14, 785–797.
- Laudadio, V. and Tufarelli, V. (2010) Treated fava bean (*Vicia faba* var. *minor*) as substitute for soybean meal in diet of early phase laying hens: egg-laying performance and egg quality. *Poultry Science* 89, 2299–2303.
- Lugtenberg, B. and Kamilova, F. (2009) Plant-growth-promoting rhizobacteria. *Annual Review of Microbiology* 63, 541–556.
- Lupwayi, N.Z., Lafond, G.P., May, W.E., Holzapfel, C.B. and Lemke, R.L. (2012) Intensification of field pea production: impact on soil microbiology. *Agronomy Journal* 104, 1189–1196.
- Maimaiti, J., Zhang, Y., Yang, J., Cen, Y.-P., Layzell, D.B., Peoples, M. and Dong, Z. (2007) Isolation and characterization of hydrogen-oxidizing bacteria induced following exposure of soil to hydrogen gas and their impact on plant growth. *Environmental Microbiology* 9, 435–444.
- Malézieux, E., Crozat, Y., Dupraz, C., Laurans, M., Makowski, D., Ozier-Lafontaine, H., Rapidel, B., deTourdonnet, S. and Valantin-Morison, M. (2009) Mixing plant species in cropping systems: concepts, tools and models. A review. *Agronomy for Sustainable Development* 29, 43–62.
- McCrary, M.A., Hamaker, B.R., Lovejoy, J.C. and Eichelsdoerffer, P.E. (2010) Pulse consumption, satiety and weight management. *Advances in Nutrition* 1, 17–30.
- Metzger, M.J., Bunce, R.G.H., Jongman, R.H.G., Mucher, C.A. and Watkins, J.W. (2005) A climatic stratification of the environment of Europe. *Global Ecology and Biogeography* 14, 549–563.
- Neumann, A., Torstensson, G. and Aronsson, H. (2011) Losses of nitrogen and phosphorus via the drainage system from organic crop rotations with and without livestock on a clay soil in southwest Sweden. *Organic Agriculture* 1, 217–229.
- O'Mara, F. (2008) *Country Pasture/Forage Resource Profile for Ireland*. Food and Agriculture Organization of the United Nations (FAO), Rome. Available at: <http://www.fao.org/ag/AGP/AGPC/doc/Counprof/PDF%20files/Ireland.pdf> (accessed 26 February 2013).

- Palander, S., Laurinen, P., Perttilä, S., Valaja, J. and Partanen, K. (2006) Protein and amino acid digestibility and metabolizable energy value of pea (*Pisum sativum*), faba bean (*Vicia faba*) and lupin (*Lupinus angustifolius*) seeds for turkeys of different age. *Animal Feed Science and Technology* 127, 89–100.
- Pappa, V.A., Rees, R.M., Walker, R.L., Baddeley, J.A. and Watson, C.A. (2011) Nitrous oxide emissions and nitrate leaching in an arable rotation resulting from the presence of an intercrop. *Agriculture, Ecosystems and Environment* 141, 153–161.
- Pelletier, N. and Tyedmers, P. (2010) Forecasting potential global environmental costs of livestock production 2000–2050. *Proceedings of the National Academy of Sciences of the USA* 107, 18371–18374.
- Peoples, M.B., Brockwell, J., Herridge, D.F., Rochester, I.J., Alves, B.J.R., Urquiaga, S., Boddey, R.M., Dakora, F.D., Bhattarai, S., Maskey, S.L., Sampet, C., Rerkasem, B., Khan, D.F., Hauggaard-Nielsen, H. and Jensen, E.S. (2009) The contributions of nitrogen-fixing crop legumes to the productivity of agricultural systems. *Symbiosis* 48, 1–17.
- Peyraud, J.L., Le Gall, A. and Lüscher, A. (2009) Potential food production from forage legume-based systems in Europe: an overview. *Irish Journal of Agricultural and Food Research* 48, 115–135.
- Phelan, P., Moloney, A.P., McGeough, E.J., Humphreys, J., Bertilsson, J., O’Riordan, E.G. and O’Kiely, P. (2015) Forage legumes for grazing and conserving in ruminant production systems. *Critical Reviews in Plant Sciences* 34, 281–326.
- Prew, R.D. and Dyke, G.V. (1979) Experiments comparing ‘break crops’ as a preparation for winter wheat followed by spring barley. *Journal of Agricultural Science, Cambridge* 92, 189–201.
- Public Health England (2016) *The Eatwell Guide*. Department of Health in association with the Welsh Assembly Government, the Scottish Government and the Food Standards Agency in Northern Ireland, London.
- Reckling, M., Hecker, J.-M., Bergkvist, G., Watson, C.A., Zander, P., Schläfke, N., Stoddard, F.L., Eory, V., Topp, C.F.E., Maire, J. and Bachinger, J. (2016a) A cropping assessment framework – evaluating effects of introducing legumes into crop rotations. *European Journal of Agronomy* 76, 186–197.
- Reckling, M., Bergkvist, G., Watson, C.A., Stoddard, F.L., Zander, P.M., Walker, R., Pristeri, A., Toncea, I. and Bachinger, J. (2016b) Trade-offs between economic and environmental impacts of introducing legumes into cropping systems. *Frontiers in Plant Science* 7, 669.
- Renna, M., Cornale, P., Lussiana, C., Malfatto, V., Fortina, R., Mimosi, A. and Battagliani, L.M. (2012) Use of *Pisum sativum* (L.) as alternative protein resource in diets for dairy sheep: effects on milk yield, gross composition and fatty acid profile. *Small Ruminant Research* 102, 142–150.
- Robson, M.C., Fowler, S.M., Lampkin, N.H., Leifert, C., Leitch, M., Robinson, D., Watson, C.A. and Litterick, A.M. (2002) The agronomic and economic potential of break crops for ley/arable rotations in temperate organic agriculture. *Advances in Agronomy* 77, 369–427.
- Scalbert, A., Manach, C., Morand, C., Remesy, C. and Jimenez, L. (2005) Dietary polyphenols and the prevention of diseases. *Critical Reviews in Food Science* 45, 287–306.
- Schreurs, N.M., McNabb, W.C., Tavendale, M.H., Lane, G.A., Barry, T.N., Cummings, T., Fraser, K., López-Villalobos, N. and Ramírez-Restrepo, C.A. (2007) Skatole and indole concentration and the odour of fat from lambs that had grazed perennial ryegrass/white clover pasture or *Lotus corniculatus*. *Animal Feed Science and Technology* 138, 254–271.
- Sirtori, C.R., Galli, C., Anderson, J.W. and Arnoldi, A. (2009) Nutritional and nutraceutical approaches to dyslipidemia and atherosclerosis prevention: focus on dietary proteins. *Atherosclerosis* 203, 8–17.
- Sirtori, C.R., Triolo, M., Bosisio, R., Bondioli, A., Calabresi, L., De Vergori, V., Gomaraschi, M., Mombelli, G., Pazzucconi, F., Zacherl, C. and Arnoldi, A. (2012) Hypocholesterolaemic effects of lupin protein and pea protein/fibre combinations in moderately hypercholesterolaemic individuals. *British Journal of Nutrition* 107, 1176–1183.
- Steinshamn, H. (2010) Effect of forage legumes on feed intake, milk production and milk quality – a review. *Animal Science Papers and Reports* 28, 195–206.

- Stevenson, F.C. and van Kessel, C. (1997) Nitrogen contribution of pea residue in a hummocky terrain. *Soil Science Society of America Journal* 61, 494–503.
- Stoddard, F.L. (2013) Novel feed and non-food uses of legumes. Legume Futures Report 1.3. Available at: www.legumefutures.de (accessed 30 September 2016).
- Stoddard, F.L., Hovinen, S., Kontturi, M., Lindström, K. and Nykänen, A. (2009) Legumes in Finnish agriculture: history, present status and future prospects. *Agricultural and Food Science* 18, 191–205.
- Strohle, A., Waldmann, A., Wolters, M. and Hahn, A. (2006) Vegetarian nutrition: preventive potential and possible risks part 1: Plant foods. *Wiener Klinische Wochenschrift* 118, 580–593.
- Subramaniyan, S. and Vadivelu, S. (1990) Effects of *Crotalaria spectabilis* extracts on *Meloidogyne incognita*. *International Nematology Network Newsletter* 7, 8–9.
- Tacon, A.G.J., Hasan, M.R. and Metian, M. (2011) Demand and supply of feed ingredients for farmed fish and crustaceans. Trends and prospects. Food and Agriculture Organization of the United Nations (FAO) Fisheries and Aquaculture Technical Paper 564. FAO. Rome.
- Thomsen, M.H. and Hauggaard-Nielsen, H. (2008) Sustainable bioethanol production combining biorefinery principles using combined raw materials from wheat undersown with clover-grass. *Journal of Industrial Microbiology and Biotechnology* 35, 303–311.
- Thorup-Kristensen, K. (1993) Root growth of nitrogen catch crops and of a succeeding crop of broccoli. *Acta Agriculturae Scandinavica Section B: Soil and Plant Science* 43, 58–64.
- Tosti, G., Benincasa, P., Farneselli, M., Tei, F. and Guiducci, M. (2014) Barley–hairy vetch mixture as cover crop for green manuring and the mitigation of N leaching risk. *European Journal of Agronomy* 54, 34–39.
- Trushenski, J.T., Kasper, C.S. and Kohler, C.C. (2006) Challenge and opportunities in finfish nutrition. *North American Journal of Aquaculture* 68, 122–140.
- Tuulos, A., Yli-Halla, M., Stoddard, F.L. and Mäkelä, P.S.A. (2014) Winter turnip rape as a soil N scavenging catch crop in a cool humid climate. *Agronomy for Sustainable Development* 35, 359–366.
- Valtion Ravitsemusneuvottelukunta (VRN) (2014) Nutrition Recommendations. Available at: <http://www.ravitsemusneuvottelukunta.fi/portal/en/nutrition+recommendations/> (accessed 30 March 2016).
- Vander Pol, M., Hristov, A.N., Zaman, S. and Delano, N. (2008) Peas can replace soybean meal and corn grain in dairy cow diets. *Journal of Dairy Science* 91, 698–703.
- Vicenti, A., Toteda, F., Di Turi, L., Cocca, C., Perrucci, M., Melodia, L. and Ragni, M. (2009) Use of sweet lupin (*Lupinus albus* L. var. Multitalia) in feeding for Podolian young bulls and influence on productive performances and meat quality traits. *Meat Science* 82, 247–251.
- Volpelli, L.A., Comellini, M., Masoero, F., Moschini, M., Lo Fiego, D.P. and Scipioni, R. (2010) Faba beans (*Vicia faba*) in dairy cow diet: effect on milk production and quality. *Italian Journal of Animal Science* 9, 138–144.
- Waghorn, G. (2008) Beneficial and detrimental effects of dietary condensed tannins for sustainable sheep and goat production: progress and challenges. *Animal Feed Science and Technology* 147, 116–139.
- Wang, D., Lebauer, D.S. and Dietze, M.C. (2010) A quantitative review comparing the yield of switchgrass in monocultures and mixtures in relation to climate and management factors. *Global Change Biology Bioenergy* 2, 16–25.
- Westhoek, H., Rood, T., van deBerg, M., Janse, J., Nijdam, D., Reudink, M. and Stehfest, E. (2011) *The Protein Puzzle*. PBL Netherlands Environmental Assessment Agency: The Hague, the Netherlands.
- White, G.A., Smith, L.A., Houdijk, J.G.M., Homer, D., Kyriazakis, I. and Wiseman, J. (2015) Replacement of soya bean meal with peas and faba beans in growing/finishing pig diets: effect on performance, carcass composition and nutrient excretion. *Animal Feed Science and Technology* 209, 202–210.
- Yan, L., Penttinen, P., Simojoki, A., Stoddard, F.L. and Lindström, K. (2015) Perennial crop growth in oil-contaminated soil in a boreal climate. *Science of the Total Environment* 532, 752–761.

2

The Role of Legumes in Bringing Protein to the Table

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Abstract

This chapter examines the role of legumes in the provision of nitrogen and protein in the European food system. It follows the nitrogen cycle starting with a description of biological nitrogen fixation (BNF) and its role in generating reactive nitrogen that is essential to the functioning of ecosystems. From this, it describes the role of legumes in supplying protein for food and feed from this reactive nitrogen. A detailed account of sources and uses of plant protein in Europe is provided, including a consideration of the effect of diet. Grain legumes are lower yielding than cereals. Cereals, which are particularly high yielding in Europe, dominate most European cropping systems. BNF and protein formation are demanding in terms of plant energy (photosynthate) but this does not fully explain the difference in yield between cereals and legumes. The high yield of cereals has had a profound impact on European agricultural systems. Through the combination of fertilizer nitrogen, imported protein-rich crop commodities and specialization in high-yielding cereal production, Europe has achieved self-sufficiency in temperate foodstuffs, including commodities required to support high consumption of meat and dairy products. Cropping in the European Union (EU) is dominated by cereals and 57% of the cereals grown are fed to animals in the EU. The growth in the demand for plant protein by the expanding livestock sector has resulted in a 71% deficit in high-protein crop commodities, 87% of which is filled by imported soybean or soybean meal. Through the close relationship between this deficit and the production of livestock, European dietary patterns have profound implications for the global nitrogen cycle. A reduction in the production of livestock products from the current high level in Europe, in line with a reduction in consumption towards official health recommendations, has been estimated to reduce nitrogen pollution emissions from farming by about 40% and the demand for imported soy by 75%. If reducing the protein deficit is a priority, an integrated approach combining agricultural, environmental, food and trade policies is required.

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Introduction

Proteins are large organic molecules that are essential to life. Proteins catalyse a wide range of biological reactions and are the main component of muscle tissue. Protein is also essential for photosynthesis, so leafy plant material is protein-rich. Storage proteins located in seeds, tubers and other plant storage organs that support plant reproduction are the source of traded protein in our feed and food. The building blocks of proteins, amino acids, are nitrogen-based compounds (containing about 16% nitrogen). Proteins account for most of the nitrogen in living organisms. This nitrogen is provided to higher plants in a reactive or 'fixed' form such as ammonium or nitrate derived through fixation from inert nitrogen (N_2) in the atmosphere. Rhizobia, which are bacteria hosted as symbionts on legume roots, fix atmospheric nitrogen. Legumes are the major source of reactive nitrogen in natural ecosystems. Due to the ready supply of nitrogen, legumes are also rich in protein. Legumes therefore play a critical role in the nitrogen cycle and in the supply of protein, both in natural ecosystems and in farming systems, especially where the use of fertilizer nitrogen is restricted. The purpose of this chapter is to describe the link between these fundamental nitrogen-related ecological processes and the functioning of our food system, and to derive conclusions for the development of legume-supported cropping systems.

Legumes: the Mainstay of Protein Provision in Natural Terrestrial Ecosystems

Dinitrogen (N_2) in air is inert, and splitting and reducing it to generate reactive nitrogen available for biological processes requires substantial inputs of energy in the three major pathways: (i) atmospheric fixation taking place in lightning; (ii) biological fixation; and (iii) industrial or synthetic fixation. In synthetic nitrogen fixation, hydrogen, usually derived from methane (CH_4) in natural gas, is combined with nitrogen at high temperature and pressure in the Haber–Bosch process. For fertilizer production, ammonia is usually converted to urea or ammonium nitrate and the total energy required is about 49 MJ/kg fertilizer nitrogen (Fehrenbach *et al.*, 2007), or the equivalent of about 1 kg of natural gas.

Biological nitrogen fixation (BNF) depends on only a few types of microorganisms: (i) rhizobia bacteria (of the family Rhizobiaceae) on legumes; (ii) actinomycetes (*Frankia* spp.) on about 200 woody species belonging to eight angiosperm families such as *Alnus* spp.; (iii) free-living soil bacteria (*Azotobacter*, *Azomonas*, *Clostridium*, *Citrobacter* and others); and (iv) cyanobacteria that are either symbiotic (*Anabaena* spp. with the aquatic fern *Azolla* spp.) or free-living. In this BNF, atmospheric N_2 is reduced to ammonia (NH_4^+) through the bacterial nitrogenase enzyme system. In mixed plant communities, the fixed nitrogen in legumes becomes available to the other plants through root exudates, by degradation of senescent organs, or via the excretions of animals grazing on the legume.

Supported by BNF, legumes are very effective pioneering plants. Legume species of the genus *Genista* (brooms) are so closely associated with colonizing new

soils that the common and Latin names of one, *Genista aetnensis* (Mount Etna broom), refer to the mountain where it is a prominent feature of vegetation on old lava flows (Fig. 2.1). Legumes remain common in natural plant communities beyond the pioneering stage, and most of the nitrogen in natural and semi-natural ecosystems, including that in animal protein, is ultimately derived from legumes.



Fig. 2.1. The pioneer character of legumes is clearly exhibited by Mount Etna broom (*Genista aetnensis*), so named because of its prevalence on old lava flows on the lower slopes of Mount Etna. (Photo credit: Velela on Wikimedia.)

The partnership between legumes and rhizobia

BNF in legumes depends on effective symbiosis between the host legume plant and the rhizobium. Rhizobia are relatively specific to their host legumes. Lucerne (alfalfa; *Medicago* spp.) and sweet clovers (*Melilotus* spp.) are associated with *Sinorhizobium meliloti*; clovers (*Trifolium* spp.) with *Rhizobium leguminosarum* biovar. *trifolii*; pea (*Pisum* spp.), vetches (*Vicia* spp.) including faba bean (*Vicia faba*) and lentil (*Lens culinaris*) with *R. leguminosarum* bv. *viciae*, common bean (*Phaseolus vulgaris*) with *R. leguminosarum* bv. *phaseoli*; soybean (*Glycine max*) with *Bradyrhizobium japonicum*, lupin (*Lupinus* spp.) with *Bradyrhizobium* 'sp.'; and bird's foot trefoil (*Lotus* spp.) with *Mesorhizobium loti* (Amarger, 2001).

The compatible rhizobia enter the plant via plant-derived infection threads and occupy root cells to form the nitrogen-fixing nodule. The nitrogen-fixing enzyme nitrogenase is produced within the bacterium, and red leghaemoglobin (a molecule similar to the haemoglobin) in the cytoplasm of the root nodule cell controls the flow of oxygen to the bacteria. As a result, active nodules have characteristic pink centres. Nitrogenase is active as long as the plant is metabolizing, even close to 0°C (Lindström, 1984; Stoddard *et al.*, 2009).

Enhancing fixation

The use of inoculation with the 'right' rhizobium for a given legume is an important production technology in some situations. For pea, faba bean and clover, rhizobia native to European agricultural soils are generally regarded as sufficient to establish symbiosis, but inoculation of seed with improved selections can increase BNF, particularly where a crop is new to a site, or where the soil pH is low (van Kessel and Hartley, 2000; Lindström *et al.*, 2010). Inoculation of lucerne where it has not been cropped for a long period is often beneficial. Even where the same inoculant species infects several hosts, there are differences between bacterial strains, so the isolate of *R. leguminosarum* used on pea differs from that used on faba bean or clover. Selections (biovars) of *R. leguminosarum* have been identified that optimize the amount of nitrogen fixed by each host species (Lindström, 1984; Stoddard *et al.*, 2009). Inoculation with *Bradyrhizobium japonicum* is considered essential for optimal nitrogen fixation in soy (see Chapter 7, this volume).

There are several methods of inoculating legumes, and inoculants often require special care to maintain their viability. Furthermore, rhizobial inoculants and grain legumes must match to realize the BNF benefits. Other non-rhizobial bacteria such as plant growth-promoting bacteria can also improve nodulation and grain yield with co-inoculation with crop-specific rhizobia (Tariq *et al.*, 2014). However, inoculation of seed is not always useful. When the population of indigenous root-nodule bacteria for the given crop is high, they can out-compete the introduced inoculant bacteria (Thies *et al.*, 1991). The survival of the indigenous population of *R. leguminosarum* is affected by soil pH (Leinonen, 1996), so soil pH is a good indicator of the potential survival of rhizobia.

Costs of biological nitrogen fixation

Analogous to synthetic nitrogen fixation, BNF requires energy. Each molecule of atmospheric nitrogen (N_2) fixed by conversion to two ions of NH_4^+ (ammonium), requires 16 molecules of ATP (the molecule that transfers energy within cells), representing a cost of 10–15 g glucose per gram of nitrogen fixed (Hay and Porter, 2006). This energy cost is met by the legume plant in the form of photosynthate supplied to the rhizobia and this has consequences for the yield of legumes compared with cereals and other non-leguminous plants fertilized using synthetic nitrogen fertilizer or manures.

However, there are compensating effects. The availability of biologically fixed nitrogen obviates the need to reduce nitrate to ammonium, which avoids a cost of 4–5 g glucose per gram of nitrogen (Hay and Porter, 2006), a saving estimated to be equivalent to 10 g glucose per gram of nitrogen in faba bean (Schilling *et al.*, 2006). This partly compensates for the energy cost of the BNF. Vertregt and Penning de Vries (1987) reported that BNF has a net cost of 4.5 g glucose per gram of nitrogen fixed. The overall effect on crop yield potential depends on whether the growth of the plant is limited by its ability to photosynthesize ('source limited') or by its ability to use the photosynthate for new plant tissue ('sink limited'). In faba bean and soybean, rhizobial symbiosis uses 4–16% of the host plant photosynthate, but this can be compensated by an increased photosynthetic rate (source) as the plant responds to the demand (sink). The increased demand stimulates photosynthesis so the net yield penalty of BNF is zero (Kaschuk *et al.*, 2009). In pea, yield was found to be source limited, and a significant yield penalty attributable to BNF was shown (Schulze *et al.*, 1994). Crops subjected to stresses are source limited, and in these cases there is a negative effect of BNF on yield, on top of that caused by the stress itself. A review concluded that legumes produce about 15% less above-ground biomass per unit of photosynthetically active radiation intercepted than carbohydrate-rich crops (Gosse *et al.*, 1986) but much of this can be accounted for by the higher energy requirements of protein synthesis. The synthesis of protein requires about 60% more glucose than the synthesis of starch (Penning de Vries *et al.*, 1974) even though the energy content of starch and protein is the same. This, and the energy cost of BNF, only partly explains why grain legumes are lower yielding than cereal crops (Table 2.1).

Quantity and Fate of Fixed Nitrogen

Estimating the quantity of nitrogen fixed by legumes is of interest to agriculturalists, environmental scientists and policy makers. Pea and faba bean were estimated to derive 60% and 74% of the nitrogen in their shoot biomass from BNF (Peoples *et al.*, 2009). However, estimating total BNF requires estimates of nitrogen in roots and released to the soil by roots. Calculations based on root:shoot ratios and root nitrogen content suggest that below-ground nitrogen is only 8–14% of above-ground nitrogen in pea, faba bean and narrow-leafed lupin (Baddeley *et al.*, 2013). Others have estimated that 30–60% of total plant nitrogen may be below ground (Peoples *et al.*, 2009), representing up to 100 kg N/ha for faba bean

(Jensen *et al.*, 2010). Some of the differences may be due to nitrogen deposited in the root zone from root exudates, shed cells and dead root fragments. Such nitrogen represented 12–16% of plant nitrogen, or 80% of below-ground nitrogen, from pea, faba bean and white lupin (Mayer *et al.*, 2003).

Table 2.2 presents data assembled by Baddeley *et al.* (2013) on a range of nitrogen-related parameters for seven grain legume species. This shows that nitrogen harvest indices are generally below 0.80, which is lower than in cereals (e.g. as reported by HGCA, 2006; Barraclough *et al.*, 2014). Therefore the high

Table 2.1. The average annual grain yield (t/ha), yield of protein, starch and oil in grain (t/ha) and the concentration of protein, starch and oil in grain for four major grain legumes and wheat and oilseed rape as two non-legume reference crops in Europe. (Crop production data from FAOSTAT, 2015; composition information from Feedipedia, 2015.)

	Yield (t/ha)				Concentration in grain (%)		
	Grain	Protein	Starch	Oil	Protein	Starch	Oil
Faba bean	2.8	0.81	1.25	0.04	29	44.7	1.4
Pea	2.7	0.68	1.39	0.03	25	51.3	1.2
White lupin	1.6	0.61	0.00	0.16	38	0.0	10.0
Soybean	2.6	1.07	0.17	0.55	41	6.4	21.3
Wheat	5.6	0.67	3.87	0.10	12	69.1	1.7
Oilseed rape	3.1	0.63	0.11	1.43	21	3.4	46.1

Table 2.2. Constants and calculated values used to derive estimates of fixed nitrogen (N) and N balance for FAO^a classes of grain legumes. All calculated quantities are relative to 1 t of grain produced. (Coefficients from Baddeley *et al.*, 2013.)

Data on crop parameters relating to 1 t of grain	Faba bean	Chickpea	Lentil	Yellow lupin	Pea	Soybean	Vetches
Grain protein concentration (%)	29	22	29	36	25	40	29
Dry matter harvest index	0.49	0.31	0.42	0.44	0.51	0.52	0.34
N harvest index	0.68	0.80	0.65	0.84	0.73	0.73	0.79
Above-ground N (g/kg)	59.5	37.3	61.0	58.5	47.2	75.0	50.5
Root:shoot ratio	0.23	0.44	0.37	0.28	0.11	0.20	0.35
Root biomass production (t)	0.40	1.22	0.77	0.55	0.19	0.33	0.89
Root N concentration (%)	2.2	1.4	1.4	1.2	2.2	1.7	2.9
Root N production (kg)	8.9	17.1	10.7	6.5	4.1	5.7	25.8
Proportional rhizodeposition	0.18	0.53	0.15	0.17	0.12	0.20	0.15
Rhizodeposition (kg)	12.6	28.8	10.8	11.1	6.2	15.7	11.4
Total N production (kg)	81.1	83.2	82.5	76.1	57.4	96.5	87.7
Proportional atmospheric N	0.77	0.50	0.70	0.82	0.70	0.52	0.72
N fixed (kg/t grain)	62	42	58	62	40	50	63

^aFAO, Food and Agriculture Organization of the United Nations.

protein content in legume grain is attributable to a high nitrogen concentration in the plant generally rather than an especially high rate of transfer of nitrogen (protein) into the grain.

The data presented in [Table 2.2](#) led to estimates of rates of BNF in grain legume crops from 90 kg/ha to 170 kg/ha on the basis of average yields. Greater fixation is supported by higher yielding crops.

BNF in temperate forage legumes has been examined by Peeters *et al.* (2006). Estimates range from between 100 kg N/ha and 350 kg N/ha for white clover, and between 100 kg N/ha and 400 kg N/ha for red clover and lucerne. This nitrogen fixation supports 7–11 t dry matter (DM)/ha for white clover and grass; 9–16 t DM/ha for red clover and grass (Peeters *et al.*, 2006) and 10–15 t DM/ha for lucerne (Annicchiarico *et al.*, 2015).

Baddeley *et al.* (2013) estimated that 811,000 t of nitrogen was fixed in the European Union (EU) (not including Croatia) by agricultural legumes (grain and forage legumes) in 2009. (This compares well with the model estimate presented later in the chapter in [Fig. 2.4](#).) While this is a significant quantity of nitrogen, it is only approximately 5% of the reactive nitrogen entering Europe's farming systems (in fertilizer and imported feed). The total amount of nitrogen fixed by forage legumes was estimated to be 586,000 t, with approximately 70% from permanent pasture and 30% from temporary grassland. De Vries *et al.* (2011) estimated the total fixation by agricultural legumes at a slightly higher value of 1.12 million t based on four European nitrogen budget models that include about 5 kg/ha of nitrogen fixation by free-living microbes in all non-legume arable land.

Legumes and Our Protein Supplies

In nature, the ready supply of reactive nitrogen from BNF supports high concentrations of protein in legume plant tissues, especially in seeds. In grain legumes, seed protein concentrations range from 20% to 25% in common bean, lentil, chickpea and pea, to over 40% in soybean and yellow lupin. The higher protein concentrations are found in those legume species that store other energy in oil. This has implications for the economic competitiveness of starchy grain legumes such as faba bean and pea because a relatively low cereal price tends to depress the price of pea and faba bean due to the high proportion of starch in the seeds.

Carbohydrate-rich cereals dominate most European cropping systems. In these systems, oilseed rape and sunflower are the dominant alternative to cereals, referred to as 'break' crops because they break the sequence of cereal cropping. These oilseed break crops lead to higher yields in subsequent cereal crops and complement cereals with high protein and oil contents. The grain yield performance of grain legumes compared with wheat and oilseed rape is a good indicator of how well grain legumes can compete for land resources (Stoddard, 2013; de Visser *et al.*, 2014). Because these are average yields for the EU, there are many regions where the data in [Table 2.1](#) are only partly relevant. However, important generalizations can be drawn. On average, the annual yield of starch-rich grain legumes (faba bean and pea) is about half that of wheat and similar to that of oilseed rape. In order to maintain economic output, the price per tonne of grain

legumes must be substantially higher than that of wheat and comparable with oilseeds taking into account additional rotational benefits from legumes. Such a position depends on a high price for protein compared with oil and starch.

Protein quality

The quality of the protein for feeding, as determined by the amino acid composition, also plays a role in the competitiveness of legumes. Because of its amino acid profile (Table 2.3), soy is particularly highly valued for inclusion in many animal feeds and valued also because of the high digestibility of the essential amino acids. For large-scale feed manufacture, the availability of large batches shipped into Europe is an additional advantage. However, grain legume proteins generally complement cereal proteins in a similar way. They are all higher in lysine than cereals. The notable difference between soybean and other legumes is the generally higher concentrations of methionine, cysteine and tryptophan in soy protein, which combined with a high concentration of lysine provides the foundation of a well-balanced supplement in cereal-based feeds for monogastrics. There are also differences between legume species in terms of the characteristics of the fibre fraction, but all grain legume species deliver high-quality protein materials suitable for use in Europe's livestock sectors.

The recently completed GreenPig project showed clearly that pea and faba bean can be used to completely replace soy in feed for growing and fattening pigs (Houdijk *et al.*, 2013; Smith *et al.*, 2013). This good performance compared with that reported in earlier research is attributable to advances in balancing ingredients using standardized ileal digestibility (Stein *et al.*, 2005) and to the use of synthetic amino acids to optimize the amino acid profiles.

Europe's sources of plant protein

European agriculture is often characterized as being heavily reliant on imported plant protein (e.g. Häusling, 2011; USDA, 2011). For assessing the extent of the protein deficit and especially opportunities to reduce it, a wider approach examining the sourcing and use of all plant proteins is needed. To consider this, we first

Table 2.3. The concentration (%) of major limiting amino acids in the protein of four grain legume crops and two non-legume reference crops used for animal feed in Europe. (From Hazzledine, 2008.)

	Lysine	Methionine	Cysteine	Tryptophan
Faba bean	6.2	0.7	1.2	0.8
Pea	7.2	0.9	1.5	0.9
White lupin	6.2	0.7	1.2	0.9
Soybean	6.2	1.4	1.5	1.4
Wheat	2.9	1.6	2.3	1.3
Oilseed rape	5.6	2.0	2.4	1.4

examined the transfers of protein in the major traded crop commodities (Table 2.4). We estimate that the total consumption of protein derived from tradable arable crop products (import + EU production - export) was 55 million t in 2011, of which 52% is provided by cereals. Of this cereal protein, 60% is fed to animals. In addition, forage maize provided 3.9 million t, almost all for beef and milk production. There is a net export of cereals (the only major crop commodity group that has a net export) and EU cereal production in total equates to 53% of tradable protein consumption. When all supplies and trade are considered, the EU is 69% self-sufficient in tradable plant protein. Imported soy accounts for 62% of the high-protein commodities used (pulses and oilseed meals). The deficit in these high-protein commodities is 71%

Table 2.4. The European Union (EU) tradable plant protein balance – net import, EU production and use of protein in feed or food.^a

	Net import	Production	Use in animal feed	Use in food
Crop quantities (million t)				
Soybean	36.9	1.3	38.1	0.1
Oilseed rape	2.7	19.3	22.0	0.0
Sunflower seed	4.9	8.5	13.4	0.1
Other oilseeds	3.5	0.0	3.5	0.0
Pea	0.1	1.6	0.8	0.9
Faba bean	0.2	1.9	1.2	0.9
Fruit and vegetables	14.0	192.7	8.9	198.5
Cereals	-15.6	293.1	167.7	110.9
Forage maize (DM) ^b	0.0	55.0	55.0	0.0
Protein quantities (million t)				
Soybean	15.13	0.53	15.62	0.04
Oilseed rape	0.57	4.05	4.62	0.00
Sunflower seed	0.68	1.45	2.13	0.00
Other oilseeds	0.91	0.00	0.91	0.00
Pea	0.02	0.38	0.19	0.21
Faba bean	0.06	0.46	0.30	0.22
Fruit and vegetables	0.14	1.93	0.09	1.98
Cereals	-1.80	29.06	16.38	10.88
Total 'tradable' crops	15.71	37.86	40.24	13.33
Forage maize	0.0	3.85	3.85	0.0
Total from arable crops	15.71	41.71	44.09	13.33

^aThe data are derived from FAOSTAT (2015), accessed in January 2015. Data on soy, rapeseed and sunflower meal were converted to seed equivalents using the following conversion factors: soy 1.25; oilseed rape 1.83; sunflower 2.27. The protein contents of the seed quantities so derived come from Feedipedia (2015) as follows: soy 41%; oilseed rape 21%; sunflower 17%; pea 25%; faba bean 29%; fruit and vegetables (including starch crops) 1%. The estimate of forage maize production comes from Rüdelsheim and Smets (2011) adjusted for the maize area in Germany used for biogas production by reducing the total area from 5.0 million ha to 4.6 million ha. The forage maize yield is assumed to be 12 t dry matter/ha with a protein content of 7% (from Feedipedia, 2015). Data for some co-products of the food sector such as dried distillers grains with solubles (DDGS), sugarbeet pulp, and food waste recycled into animal feed are not considered because of lack of data. FEFAC (2014) estimate that about 17 million t of such material are used in compound feed manufacture.

^bDM, Dry matter.

and imported soy meets 87% of that deficit. These data confirm other assessments based on industry data that the EU deficit in high-protein materials is around 70%. Houdijk *et al.* (2013) reported a deficit of 68% for 2011 in the EU.

The total agricultural area of the EU (EU-27) was 185 million ha in 2012, of which about 67 million ha is grassland (FAOSTAT, 2015) (i.e. 36% of the agricultural area). These grasslands make a substantial contribution to the total protein production in Europe. They are mainly transformed into meat and milk produced by cattle, sheep and other ruminants for human consumption. The total protein production from EU grasslands is estimated here on the basis of two assumptions on yields (based on expert opinion): annual average production of 4 t DM/ha or 6 t DM/ha (Table 2.5). It must be emphasized that there are few relevant data available on the productivity of European grasslands and the assumptions made in Table 2.5 are based on our expert opinion. There are great uncertainties about the efficiency of grazing. This estimates that the total protein harvested (including grazing) from grassland is between about 40 million t and 60 million t, which compares with 42 million t from arable and permanent crops (Table 2.4).

Combining these data, the total plant protein consumption in the EU ranges from approximately 100 million t to 120 million t. A net import of 16 million t accounts for 13–16% of total protein supplies where protein from grassland is included.

Table 2.5. Protein production from European permanent and temporary grasslands on the basis of two yield assumptions.^a

	Average/total	Grazed grass	Grass silage	Hay
Utilization assumption (grazed, silage, hay %)	100	66.7	16.7	16.7
Crude protein content (%) (Erwing, 1997)	–	16.0	13.0	10.4
Grassland area (EU-27) (Eurostat, 2013) (million ha)	67.6	45.1	11.3	11.3
Production assumption 1 (4 t/ha, DM basis) ^b	4.0	4.0	5.0	3.0
Crude protein yield (t/ha)	0.59	0.64	0.65	0.32
Total protein production (million t)	39.9	28.9	7.3	3.5
Production assumption 2 (6 t/ha, DM basis)	6.0	6.0	7.0	5.0
Crude protein production (t/ha)	0.88	0.96	0.91	0.52
Total crude protein production (million t)	59.5	43.2	10.2	5.9

^aThe authors emphasize the uncertainty in the assumptions made in this table. The assumed yields are an average for all grassland in the EU, which includes unproductive semi-natural grassland on the British Isles, short-season grassland in Scandinavia, and grassland subject to heat and drought stress in the Mediterranean region. While the assumption of 4 t/ha DM might appear low, it is supported by estimates cited by FEFAC (2014).

^bDM, Dry matter.

The use of soy in European livestock production

There are no official data on the use of soy in the various livestock sectors but estimates have been made. Gelder *et al.* (2008) estimated the allocation of the soy to species based on feed formulation and farm practice in the Netherlands with inclusion rates in concentrate feed of 37%, 29%, 22% in feeds for broilers, pigs and laying hens, respectively. The inclusion of soy in beef and dairy concentrate feeds is lower at 14% and 10%, respectively. These estimates indicate that monogastrics (pigs and poultry) account for at least 80% of soybean meal use in the Netherlands. This results in the following rates of use on a per unit food commodity output basis: beef, 232 g/kg; milk, 21 g/kg; pork, 648 g/kg; poultry meat, 967 g/kg; eggs, 32 g/egg.

Because of the lack of official species-specific data, there is great uncertainty in these estimates. The total industrial feed production in Europe was 155 million t in 2013 (FEFAC, 2014). Our assessment of the FEFAC (European Feed Manufacturers' Federation) data suggests that inclusion rates of soy in feed is lower across the EU than suggested by Gelder *et al.* (2008) for the Netherlands, particularly for the monogastrics. This is reflected in the estimates provided by Westhoek *et al.* (2011).

Research in regions affected by nutrient surpluses caused by concentrated livestock production show that there is substantial scope to reduce the soybean meal and the total protein content of compound feeds without affecting animal performance. From farm practice, Linder Mayer (2015) reported that soybean meal inclusion rates for pig fattening can be reduced to 10% with substantial reduction in nitrogen excretion while maintaining animal productivity. There is even greater scope for reducing soybean meal use in ruminants that not only digest cellulose-based feeds such as grass which provides protein, but also synthesize amino acids from non-protein nitrogen compounds in their digestive system. This means that for protein supplementation, alternatives to soybean meal are more easily adopted in milk, beef and sheep production.

Europe's Evolving Agri-food System

To understand the related roles of nitrogen and legumes in the European food system, it is useful to examine changes in food consumption and production that have occurred in recent decades. A number of forces have come together since 1960: (i) changes in trade policy; (ii) technical change in livestock production; and (iii) economic growth leading to increased disposable income. Between 1961 and 2011, livestock production in Europe increased in line with consumption from the equivalent of 822 kcal/capita/day to 993 kcal/capita/day with 395% and 170% increases in poultry and pig meat, respectively (FAOSTAT, 2015). This was facilitated by intensification in production, particularly for pigs and poultry, associated with a decoupling of livestock production from the land resource base. The FAOSTAT reports that between 1961 and 2008, the number of pigs and chickens increased significantly in the EU (63% and 56%, respectively) but there was an 11% reduction in the number of cattle and sheep. The increases

in livestock numbers were less than the increase in output due to increases in productivity per animal. Changes in trade policy gave European farmers access to low-cost soy, which in effect reduced the value of home-grown sources of protein in Europe – including protein from grassland. Changes in soy imports align with changes in livestock production, particularly pigs and poultry (Fig. 2.2). Access to compound feeds and some technical developments in animal housing allowed a regional concentration of livestock production (Fig. 2.3), particularly pigs and poultry with very significant nitrogen and phosphorus pollution challenges and reduced opportunities for legume production in these regions. This scale of livestock production, based largely on European-grown cereals, is facilitated by the complementary qualities of soybean meal. Approximately 60% of Europe’s cereal harvest is now used to feed livestock.

Changes in cropping

The proportion of the EU arable area under cereals has remained remarkably stable at about 57% of the annually cropped area. Between 1961 and 2011, the maize area more than doubled, and the area of oilseed rape and sunflower increased from 1.3 million ha to 11.2 million ha (13% of arable cropping). Grain legume areas declined from 5.8 million ha in 1961 (4.7% of the arable area) to 1.9 million ha in 2011 (1.8% of the arable area).

While FAOSTAT data indicate that the proportion of EU agricultural land under grass has remained stable overall, Eurostat data show that between 1970

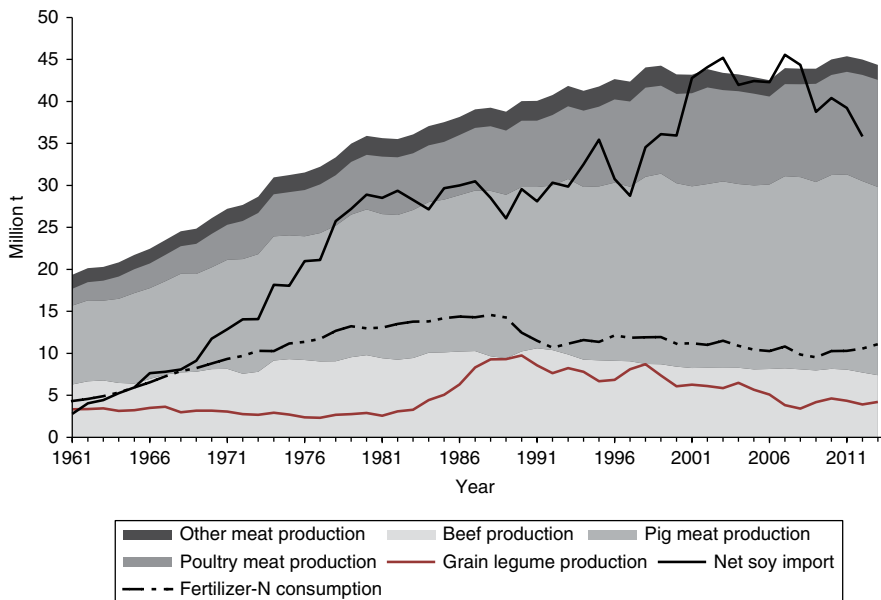


Fig. 2.2. Changes in the production of meat and corresponding changes in fertilizer nitrogen use, protein crop production and net soy import for the EU-27 (1961–2011). (From calculations based on data from FAOSTAT, 2015.)

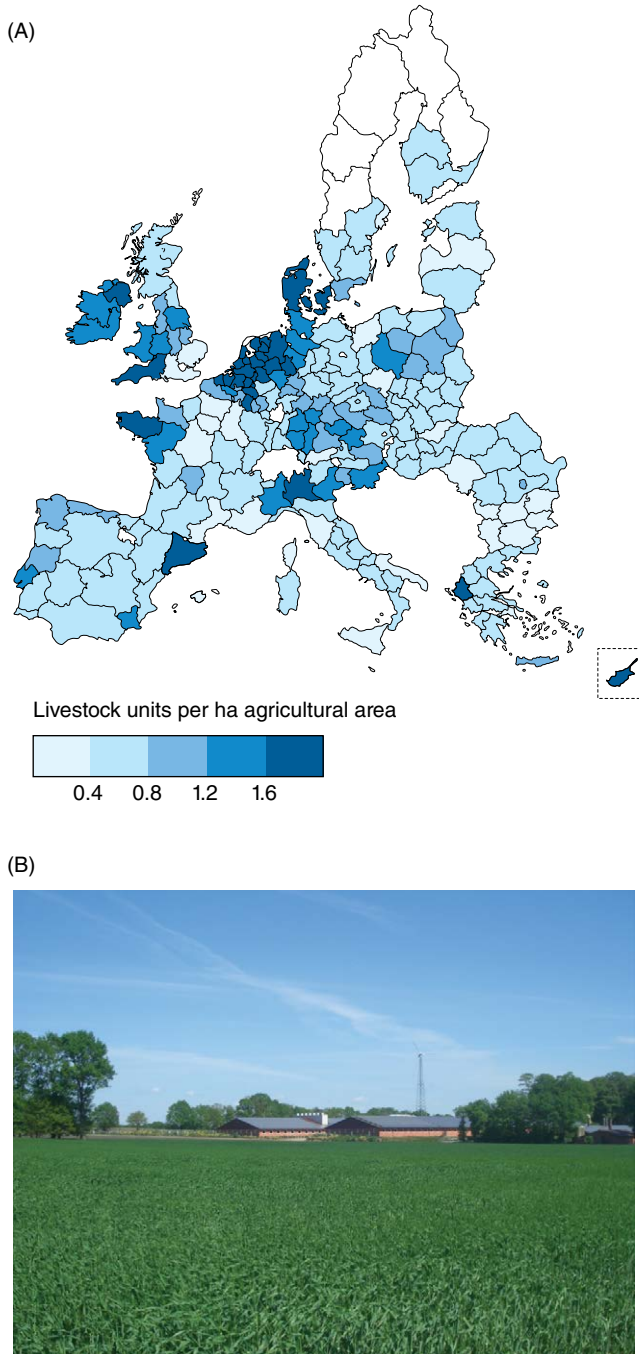


Fig. 2.3. Increased and concentrated livestock production, particularly pigs and poultry, has had consequences for the demand for concentrate feeds (including soy) and the nitrogen cycle. (A) Variation in regional livestock densities across Europe. (B) Intensive pig production in north-west Germany combined with specialization in carbohydrate-rich cereals crops (in this case rye).

and 2012, about 9.6 million ha of permanent grasslands (about 36% of 1970 levels) were lost in the founding six member states of the EU (Eurostat, 2013).

The annual increase in cereal productivity of about 0.15 t/ha (Supit, 1997), facilitated by the switch to autumn sowing, fertilizers and plant protection products, has probably been an important factor in promoting conversion of grassland to arable cropping. The rate of increase in yield of cereals was higher than that of grain legumes in most regions (Stoddard, 2013), reinforcing the dominant position of cereals. Intensification, driven by the comparative advantage of specialization, has resulted in more concentrated production and more homogeneous farming systems.

Trade policy also had a large effect. The 'Dillon Round' of the General Agreement on Tariff and Trade (GATT) negotiations in 1962–1963 resulted in European agreement to tariff-free imports of protein-rich feedstuff for animal feeding. These imports in effect reduced the value of European plant protein sources, compared with starch-rich crops that benefited from some market support. This situation was reinforced in 1992 in the Memorandum of Understanding on Oilseeds (often referred to as the 'Blair House Agreement') negotiated during the GATT Uruguay Round. Europe is now the second largest importer of soy (China is the largest). Imported soy accounted for about 19 million ha of land outside the EU in 2008 and is the largest cause of the EU net 'virtual' land import (39% of total virtual land imports). It corresponds to the size of the German agricultural area (von Witzke and Noleppa, 2010). This trade in soy has implications for the global carbon and nitrogen cycles and has supported land-use change, directly and indirectly leading to habitat losses and greenhouse gas (GHG) emissions in South America (Malingreau and Tucker, 1988; Fearnside, 2001, 2007; Carvalho and Batello, 2009; Murphy-Bokern, 2010).

Diet, legumes and the nitrogen cycle

Given the connection between livestock production and soy use (Fig. 2.2), what is the effect of food system change on the nitrogen cycle, and what role do legumes have in such change? Using the data from biophysical modelling reported by Westhoek *et al.* (2014) we can estimate the flows and conversions of nitrogen in the European food system (Fig. 2.4). This shows that the European agri-food system uses 17.7 million t of reactive nitrogen, 64% of which is provided in fertilizer form. About 18% is provided by BNF, dominated by BNF in soybean grown outside Europe. This 17.7 million t of nitrogen supports a flux of 87 million t of plant protein used directly or indirectly for food.

These model estimates are in reasonable agreement with our estimates based on FAOSTAT commodity data (Table 2.4). However the Westhoek *et al.* (2014) estimate for protein from grassland is significantly lower than the estimates presented in Table 2.5. In reasonable agreement with the results in Table 2.4, the EU is more than 80% self-sufficient in plant protein. According to this modelling work, about 35% of all the plant protein used is from grassland (from 36% of the utilized agricultural area). About 86% of the plant protein used is consumed by livestock.

Only about 13% of the reactive nitrogen entering the system ends up in human food. Much of the loss occurs in the conversion of plant protein to

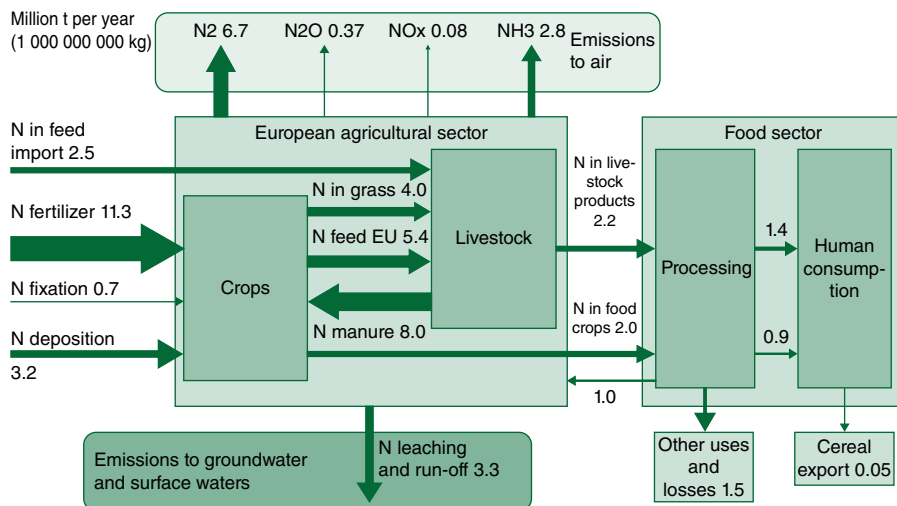


Fig. 2.4. Nitrogen (N) flows (million t/year) in the European Union (EU) agricultural and food system based on data for the EU-27 from 2004. (From Westhoek *et al.*, 2014.)

animal protein in livestock. This raises the question of the effect of dietary change on the nitrogen cycle. Westhoek *et al.* (2014) showed that a 50% reduction in the consumption and production of livestock products (which would be in line with current public health guidelines) would result in a 40% reduction in nitrogen emissions, 25–40% reduction in agricultural GHG emissions and 23% reduction in the per capita agricultural land requirement. The EU would become a larger net exporter of cereals and the use of soybean meal would be reduced by 75%. The nitrogen use efficiency (NUE) of the food system would increase from the current 18% to between 41% and 47%, depending on choices made regarding land use.

Pointers to Change in Developing the European Agri-food System

European agriculture can be characterized as reliant on a combination of reactive nitrogen in fertilizers and in imported feeds. Supported by this external input of reactive nitrogen, arable land is allocated to high-yielding cereals and oilseeds that provide the dietary energy needed. Through the combination of fertilizer nitrogen and imported protein-rich commodities, Europe has achieved remarkably high levels of self-sufficiency in temperate foodstuffs, including that required for a high level of consumption of meat and milk. This allocation of resources, with its profound implications for the nitrogen cycle, characterizes Europe's core farming activities.

Achieving higher protein independence and decreasing the negative environmental consequences of soybean imports are desirable objectives (Westhoek *et al.*, 2011; Peeters, 2012, 2013). While the European self-sufficiency in most foods is sometimes celebrated in the policy community, the public debate about soy imports

and the pollution emissions from the nitrogen cycle requires a science-based response: what are the options for change? Here we can draw conclusions directly from the analysis presented.

In line with the approach argued by Martin (2014), our calculations show that the EU has a greater protein resource than is often acknowledged. Changes in consumption, European protein production, and in the efficiency of use of protein in livestock feeding could together make a significant contribution to reducing the protein deficit. The very large effect of livestock product consumption and production on the nitrogen cycle, land use and the demand for protein-rich crop commodities means that the effect on the deficit of increased grain legume production is small compared with the effect of consumption change.

Most Europeans consume more meat and milk than is recommended for their health. Westhoek *et al.* (2014) showed clearly the consequences of this for land use, the nitrogen cycle and our soy imports. A shift towards more sustainable diets which are also healthier would have profound consequences, increase interest in grain legumes for human consumption, release land for new uses including grain legume production, and lead to a very significant reduction in the demand for soy. However, even with significant consumption change there would remain a demand for high-quality plant protein that only legumes can meet. The basic crop physiological processes that affect the yield potential in legumes only partly explain the large differences between grain legume and cereal yields in Europe. In terms of capturing solar radiation, taking into account additional photosynthetic requirements of BNF and protein production, grain legumes are physiologically less productive than cereals in Europe. This indicates that there are opportunities to increase grain legume yields. A rate of increase in grain legume yields that is faster than that of competing cereals and especially oilseeds would provide the foundation for a recovery in grain legume production in the long term.

Our analysis highlights the potential role of legumes in grassland. Even though the proportion of clover in grassland is now low, the BNF in grasslands is significant and estimated to exceed that of arable land (Baddeley *et al.*, 2013). In Chapter 9, this volume, Humphreys *et al.* highlight that increased use of white clover can be economically effective in grassland farming systems. There is considerable uncertainty in estimates of plant protein production on grassland that we provide, but we can confidently say that total plant protein production on Europe's grassland is at least similar to that on arable land, which raises the possibility of using legume-supported forage systems more intensively as a protein source. We can also infer that there is a large potential for the development of forage legumes in permanent and temporary grasslands, especially in the context of increasing prices of synthetic nitrogen fertilizer. Where converted to meat and milk, there are additional food quality benefits of forage legumes. Plant secondary compounds (PSC) in forage legumes interact with rumen microbes, resulting in higher proportions of linoleic and alpha-linolenic acid in the lipids in milk and meat (Githiori *et al.*, 2006; Jayanegara *et al.*, 2011; Willems *et al.*, 2014). Compared with grain-fed meat or milk, grass-fed meat or milk is: (i) higher in total omega-3 (and has a healthier ratio of omega-6 to omega-3 fatty acids); (ii) higher in conjugated linolenic acid (CLA) (*cis-9 trans-11*) (Dhiman *et al.*, 1999); and (iii) higher in vaccenic acid (that can be transformed into CLA) (Duckett *et al.*, 1993).

References

- Amarger, N. (2001) Rhizobia in the field. *Advances in Agronomy* 73, 109–168.
- Annicchiarico, P., Barrett, B., Brummer, E.C., Julier, B. and Marshal, A.H. (2015) Achievements and challenges in improving temperate perennial forage legumes. *Critical Reviews in Plant Science* 34, 327–380.
- Baddeley, J.A., Jones, S., Topp, C.F.E., Watson, C.A., Helming, J. and Stoddard, F.L. (2013) Biological nitrogen fixation (BNF) by legume crops in Europe. Legume Futures Report 1.5. Available at: www.legumefutures.de (accessed 30 March 2016).
- Barraclough, P.B., Lopez-Bellido, R. and Hawkesford, M.J. (2014) Genotypic variation in the uptake, partitioning and remobilisation of nitrogen during grain-filling in wheat. *Field Crop Research* 156, 242–248.
- Carvalho, P.C.F. and Batello, C. (2009) Access to land, livestock production and ecosystem conservation in the Brazilian Campos biome: the natural grasslands dilemma. *Livestock Science* 120, 158–162.
- de Visser, C.L.M., Schreuder, R. and Stoddard, F.L. (2014) The EU's dependency on soya bean import for the animal feed industry and potential for EU produced alternatives. *Oilseeds and Fats, Crops and Lipids (OCL)* 21(4), D407. Available at: <http://www.ocl-journal.org/articles/ocl/pdf/2014/04/ocl140021.pdf> (accessed 30 March 2016).
- De Vries, W., Leip, A., Reinds, G.J., Kros, J., Lesschen, J.P. and Bouwman, A.F. (2011) Comparison of land nitrogen budgets for European agriculture by various modeling approaches. *Environmental Pollution* 159, 3254–3268.
- Dhiman, T.R., Anand, G.R., Satter, L.D. and Pariza, M.W. (1999) Conjugated linoleic acid content of milk from cows fed different diets. *Journal of Dairy Science* 82, 2146–2156.
- Duckett, S.K., Wagner, D.G., Yates, L.D., Dolezal, H.G. and May, S.G. (1993) Effects of time on feed on beef nutrient composition. *Journal of Animal Science* 71, 2079–2088.
- Erwing, W.N. (1997) *The Feed Directory*. Context, Packington, UK, 118 pp.
- Eurostat (2013) Agriculture in the European Union. Statistical and economic information. Report 2013. Eurostat, European Commission, Brussels. Available at: <http://ec.europa.eu/eurostat> (accessed 2 January 2015).
- FAOSTAT (2015) Statistics Database of the Food and Agriculture Organization of the United Nations. Food and Agriculture Organization of the United Nations, Rome. Available at: <http://faostat3.fao.org/home/E> (accessed 2 January 2015).
- Fearnside, P.M. (2001) Soybean cultivation as a threat to the environment in Brazil. *Environmental Conservation* 28, 23–38.
- Fearnside, P.M. (2007) Deforestation in Brazilian Amazonia: history, rates, and consequences. *Conservation Biology* 19, 680–688.
- Feedipedia (2015) Animal Feed Resources Information System. Available at: www.feedipedia.org (accessed 9 January 2015).
- FEFAC (European Feed Manufacturers' Federation) (2014) The Compound Feed Industry in the EU Livestock Economy. Available at: www.fefac.eu (accessed 2 January 2015).
- Fehrenbach, H., Giegrich, J., Gärtner, S., Reinhardt, G. and Rettenmaier, N. (2007) Greenhouse gas balances for the German biofuels quota legislation. Methodological guidance and default values. A report prepared for the Federal Environment Agency, Germany. Institut für Energie- und Umweltforschung (IFEU), Heidelberg, Germany.
- Gelder, J.W. van, Kammeraat, K. and Kroes, H. (2008) Soy consumption for feed and fuel in the European Union. A research paper prepared for the Friends of the Earth Netherlands. Profundo Economic Research, Castricum, the Netherlands.
- Githiori, J.B., Athanasiadou, S. and Thamsbourg, S.M. (2006) Use of plants in novel approaches for control of gastrointestinal helminths in livestock with emphasis on small ruminants. *Veterinary Parasitology* 139, 308–320.

- Gosse, G., Varlet-Grancher, C., Bonhomme, R., Chartier, M., Allirand, J.M. and Lemaire, G. (1986) Production maximale de matière sèche et rayonnement solaire intercepté par un couvert végétal. *Agronomie* 6, 47–56.
- Häusling, M. (2011) Report. The European protein deficit: what solution for a long-standing problem? (2010/2111 (INI)). Committee on Agriculture and Rural Development, European Parliament, Strasbourg, France.
- Hay, R.K.M. and Porter, J.R. (2006) *The Physiology of Crop Yield*. Blackwell Publishing, Oxford.
- Hazzledine, M. (2008) *Premier Atlas Ingredients Matrix*. Premier Nutrition Products Ltd, Rugeley, UK.
- Home-grown Cereals Authority (HGCA) (2006) *The Barley Growth Guide*. HGCA, Agriculture and Horticulture Development Board, Kenilworth, Warwickshire, UK.
- Houdijk, J.G.M., Smith, L.A., Tarsitano, D., Tolcamp, B.J., Topp, C.E.F., Masey-O'Neill, H., White, G., Wiseman, J., Knightley, S. and Kyriazakis, I. (2013) Peas and faba beans as home grown alternatives for soya bean meal in grower and finisher pig diets. In: Garnsworthy, P.C. and Wiseman, J. (eds) *Recent Advances in Animal Nutrition*. Nottingham University Press, Nottingham, pp. 145–175.
- Jayanegara, A., Kreuzer, M., Wina, E. and Leiber, F. (2011) Significance of phenolic compounds in tropical forages for the ruminal bypass of polyunsaturated fatty acids and the appearance of biohydrogenation intermediates as examined *in vitro*. *Animal Production Science* 51, 1127–1136.
- Jensen, E.S., Peoples, M.B. and Hauggaard-Nielsen, H. (2010) Faba bean in cropping systems. *Review. Field Crops Research* 115, 203–216.
- Kaschuk, G., Kuyper, T.W., Leffelaar, P.A., Hungria, M. and Giller, K.E. (2009) Are the rates of photosynthesis stimulated by the carbon sink strength of rhizobial and arbuscular mycorrhizal symbioses? *Soil Biology and Biochemistry* 41, 1233–1244.
- Leinonen, P. (1996) The effects of soil properties on indigenous *Rhizobium*-population nodulating peas. *The Science of Legumes* 3, 227–232.
- Lindermayer, H. (2015) Mast: 10% Soja reichen. *TopAgrar* 2/2015. Landwirtschaftsverlag, Munster, Germany, p. 31.
- Lindström, K. (1984) Effect of various *Rhizobium trifolii* strains on nitrogenase (C₂H₂) activity profiles of red clover (*Trifolium pratense* cv. Venla). *Plant and Soil* 80, 79–89.
- Lindström, K., Murwira, M., Willems, A. and Altier, N. (2010) The biodiversity of beneficial microbe–host mutualism: the case of rhizobia. *Research in Microbiology* 161(6), 453–463.
- Malingreau, J.-P. and Tucker, C.J. (1988) Large-scale deforestation in the Southeastern Amazon Basin of Brazil. *Ambio* 17, 49–55.
- Martin, N. (2014) What is the way forward for protein supply? The European perspective. *Oilseeds and Fats, Crops and Lipids (OCL)* 21(4), D403. Available at: <http://www.ocl-journal.org/articles/occl/pdf/2014/04/occl140015.pdf> (accessed 2 January 2015).
- Mayer, J., Buegger, F., Jensen, E.S., Schloter, M. and Hess, J. (2003) Estimating N rhizodeposition of grain legumes using a 15N *in situ* stem labelling method. *Soil Biology and Biochemistry* 35, 21–28.
- Murphy-Bokern, D. (2010) Environmental impacts of the UK food economy with particular reference to WWF Priority Places and the North-east Atlantic. World Wildlife Fund (WWF) UK. Available at: www.murphy-bokern.com (accessed 2 January 2015).
- Peeters, A. (2012) Past and future of European grasslands. The challenge of the CAP towards 2020. *Grassland Science in Europe* 17, 17–32.
- Peeters, A. (2013) Global trade impacts on biodiversity and ecosystem services. In: Jacobs, S., Dendoncker, N. and Keune, H. (eds) *Ecosystem Services. Global Issues, Local Practices*. Elsevier, Amsterdam.
- Peeters, A., Parente, G. and Le Gall, A. (2006) Temperate legumes: key-species for sustainable temperate mixtures. *Grassland Science in Europe* 11, 205–220.

- Penning de Vries, F.W.T., Brunsting, A.H.M. and Van Laar, H.H. (1974) Products, requirements and efficiency of biosynthesis: a quantitative approach. *Journal of Theoretical Biology* 45, 339–377.
- Peoples, M.B., Brockwell, J., Herridge, D.F., Rochester, I.J., Alves, B.J.R., Urquiaga, S., Boddey, R.M., Dakora, F.D., Bhattarai, S., Maskey, S.L., Sampet, C., Rerkasem, B., Khan, D.F., Hauggaard-Nielsen, H. and Jensen, E.S. (2009) The contributions of nitrogen-fixing legumes to the productivity of agricultural systems. *Symbiosis* 48, 1–17.
- Rüdelshem, P.L.J. and Smets, G. (2011) Baseline information on agricultural practices in the EU maize (*Zea mays* L.). Perseus BVBA, Sint-Martens-Latem, Belgium.
- Schilling, G., Adgo, E. and Schulze, J. (2006) Carbon costs of nitrate reduction in broad bean (*Vicia faba* L.) and pea (*Pisum sativum* L.) plants. *Journal of Plant Nutrition and Soil Science* 169, 691–698.
- Schulze, J., Adgo, E. and Schilling, G. (1994) The influence of N₂-fixation on the carbon balance of leguminous plants. *Experientia* 50, 906–912.
- Smith, L.A., Houdijk, J.G.M., Homer, D. and Kyriazakis, I. (2013) Effects of dietary inclusion of peas and faba beans as a replacement for soybean meal on grower and finisher pig performance and carcass quality. *Journal of Animal Science* 91, 3733–3741.
- Stein, H.H., Pedersen, C., Wirt, A.R. and Bohlke, R.A. (2005) Additivity of values for apparent and standardized ileal digestibility of amino acids in mixed diets fed to growing pigs. *Journal of Animal Science* 83, 2387–2395.
- Stoddard, F.L. (2013) The case studies of participant expertise in Legume Futures. Legume Futures Report 1.2. Available at: www.legumefutures.de (accessed 2 January 2015).
- Stoddard, F.L., Hovinen, S., Kontturi, M., Lindström, K. and Nykänen, A. (2009) Legumes in Finnish agriculture: history, present status and future prospects. *Agricultural and Food Science* 18, 191–205.
- Supit, I. (1997) Predicting national wheat yields using a crop simulation and trend models. *Agricultural and Forest Meteorology* 88, 199–214.
- Tariq, M., Mameed, S., Yasmeen, T., Zahid, M. and Zafar, M. (2014) Molecular characterization and identification of plant growth promoting endophytic bacteria isolated from the root nodules of pea (*Pisum sativum* L.). *World Journal of Microbiology and Biotechnology* 30(2), 719–725.
- Thies, J.E., Singleton, P.W. and Bohlool, B.B. (1991) Influence of the size of indigenous rhizobial populations on establishment and symbiotic performance of introduced rhizobia on field-grown legumes. *Applied Environmental Microbiology* 57, 19–28.
- United States Department of Agriculture (USDA) (2011) EU protein deficiency. USDA Foreign Agricultural Services. GAIN Report E60050. USDA, Washington, DC.
- van Kessel, C. and Hartley, C. (2000) Agricultural management of grain legumes: has it led to an increase in nitrogen fixation? *Field Crops Research* 65, 165–181.
- Vertregt, N. and Penning de Vries, F.W.T. (1987) A rapid method for determining the efficiency of biosynthesis of plant biomass. *Journal of Theoretical Biology* 128, 109–119.
- von Witzke, H. and Noleppa, S. (2010) EU agricultural production and trade: can more efficiency prevent increasing 'land-grabbing' outside Europe? Research Report. Humboldt University Berlin, Agripol – network for policy advice, Berlin.
- Westhoek, H., Rood, T., van denBerg, M., Janse, J., Nijdam, D., Reudink, M. and Stehfest, E. (2011) *The Protein Puzzle. The Consumption and Production of Meat, Dairy and Fish in the European Union*. PBL Netherlands Environmental Assessment Agency, The Hague, 218 pp.
- Westhoek, H., Lesschen, J., Rood, T., Wagner, S., De Marco, A., Murphy-Bokern, D., Leip, A., van Grinsven, H., Sutton, M. and Oenema, O. (2014) Food choices, health and environment: effects of cutting Europe's meat and dairy intake. *Global Environmental Change* 26, 196–205.
- Willems, H., Kreuzer, M. and Leiber, F. (2014) Alpha-linolenic and linoleic acid in meat and adipose tissue of grazing lambs differ among alpine pasture types with contrasting plant species and phenolic compound composition. *Small Ruminant Research* 116, 153–164.

3

Nitrogen and Phosphorus Losses from Legume-supported Cropping

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Abstract

The loss of nutrients from agricultural systems is recognized as a major environmental problem, contributing to air pollution and nutrient enrichment in rivers and oceans. The use of legumes within agriculture provides an opportunity to reduce some of these losses in ways which maintain or enhance agricultural productivity. This chapter considers the role of legumes in crop rotations, legumes in intercrops and legume-based green manures in influencing nutrient loss and turnover. Nitrous oxide emissions are particularly important here given that they are the largest contributor to greenhouse gas emissions from many agricultural systems. There are many circumstances in which the use of legume-supported cropping systems can reduce overall nitrous oxide emissions and the biological nitrogen fixation process associated with legumes can replace synthetic nitrogen fertilizer use.

Introduction

The efficiency of nitrogen (N) fertilizer application in agroecosystems is often no higher than 50% with 45–50% of the N applied being taken up by the crop for growth and the remaining N being lost primarily through the combined processes of denitrification, ammonia volatilization and leaching (Smil, 1999; Crews and Peoples, 2004). Using legumes in cropping systems reduces reliance on inorganic N fertilizer but in many cases the problem of low efficiency of N use remains. Through their ability to fix N, legumes play a significant role in N supply in both natural ecosystems and agriculture/agroforestry contributing as much as 500 kg N/ha/year (Briggs *et al.*, 2005). The potential environmental and agronomic implications of biological fixation have been reviewed recently by Jensen and

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Hauggaard-Nielson (2003), Muñoz *et al.* (2010) and Jensen *et al.* (2011). Positive environmental effects of legume cropping arise from a reduced reliance on inorganic N fertilizer and improvements in soil structure from residue incorporation. Negative effects are primarily associated with N losses to the atmosphere and groundwater where peaks in available N from mineralization of N-rich residues occur at periods of low crop growth or high rainfall. Soil acidification may also prove problematic, eventually leading to decreases in crop productivity, but here liming of soils is an effective treatment although affecting N losses too (Galbally *et al.*, 2010). This chapter provides a review of recent literature on N losses from legume crops and highlights management options that may reduce nitrous oxide (N_2O) emissions to the atmosphere. In addition enhanced phosphorus (P) uptake is considered particularly in respect to legume intercropping.

Nitrous Oxide Production in Agricultural Soils

Agriculture, forestry and other land use are estimated to account for 24% of anthropogenic greenhouse gas (GHG) emissions (Edenhofer *et al.*, 2014). The agricultural sector is a particularly important source of emissions of methane (CH_4) and N_2O globally, these two GHGs being approximately 25 and 298 times more effective at causing warming of the climate than carbon dioxide (CO_2). In addition atmospheric N_2O plays a significant role in depletion of the tropospheric ozone layer.

Analysis of air trapped in ice cores shows that levels of N_2O range from interglacial values of 270 parts per billion by volume (ppbv) to lower glacial values of 200 ppbv (Sowers, 2001; Fluckiger *et al.*, 2004). Since approximately 1850 though, the concentration of N_2O increased to over 280 ppbv by 1905, to over 300 ppbv by the mid-1970s and currently the atmospheric concentration of N_2O exceeds 320 ppbv, representing approximately 6% of the present-day greenhouse effect (IPCC, 2007) and 60% of global agricultural emissions of GHGs (Prather *et al.*, 2001; Smith *et al.*, 2007).

A measure of the present-day imbalance between sources and sinks for N_2O is provided in Fowler *et al.* (2009), and serves to highlight the role of agriculture in N_2O production (Table 3.1). Of the imbalance between sources and sinks, 70% can be attributed to increased N_2O production from agriculture, primarily a consequence of the addition of reactive N fertilizer to soils (Kroeze, 1999). Synthetic N fertilizer use has increased by over 800% between the years 1960 and 2000 (Fixen and West, 2002) and this trend will probably continue. Agricultural N_2O emissions are predicted to rise by 30–60% over the next 20 years, driven by a steadily increasing population and subsequent stresses on food demand leading to increased N inputs into agricultural systems through synthetic fertilizers, manure, human waste and N_2 fixing crops (Smith, 1997; Bruinsma, 2003).

N_2O production in soils reflects both the oxidation and the reduction of inorganic N forms by a wide range of soil microorganisms (fungi, bacteria and archaea). These have evolved to use inorganic N compounds as essential components of energy-coupled, electron transport systems. The rate of N_2O production is determined by a wide range of factors, but primarily the microbial capacity of

the soil, temperature, pH, substrate supply and the degree of oxygenation of the soil (Flessa *et al.*, 2002; Khalil *et al.*, 2002; Šimek and Cooper, 2002; Smith *et al.*, 2003; Malhi *et al.*, 2006; Ding *et al.*, 2007). In addition, the diffusive properties of the soil will affect the flux rate of N_2O to the atmosphere (Fig. 3.1). Water-filled pore space (WFPS) is frequently highlighted in the literature as the most important controlling variable in agricultural soils as it is directly linked with aeration and oxygen availability (Davidson, 1991; Davidson *et al.*, 2000; Smith *et al.*, 2003). In general, N_2O production is thought to be greatest at intermediate WFPS values in the range of 50–80% (Davidson, 1991; Dobbie and Smith, 2003a) with peak denitrification rates (N reduction pathways) being favoured by high WFPS values (80–85%) where reduced oxygen availability is also coupled to increased solubility

Table 3.1. Sources and sinks of nitrous oxide (N_2O) accumulation in the atmosphere. (Adapted from Fowler *et al.*, 2009.)

Sources	10^6 t N_2O /year	Sinks	10^6 t N_2O /year	Source–sinks 10^6 t N_2O /year
Oceans	3.8 (1.8–5.8)	Stratosphere	12.5 (1.8–5.8)	
Atmosphere	0.6 (0.3–1.3)	Soils	1.5–3.0	
Soils	6.6 (3.3–9.0)			
<i>Agriculture</i>	<i>2.8 (1.7–4.8)</i>			
Biomass burning	0.7 (0.2–1.0)			
Energy and industry	0.7 (0.2–1.8)			
Others	2.5 (0.9–4.1)			
<i>Total sources</i>	<i>17.7 (8.5–27.7)</i>	<i>Total sinks</i>	<i>14.0 (11.5–18.0)</i>	<i>3.7</i>

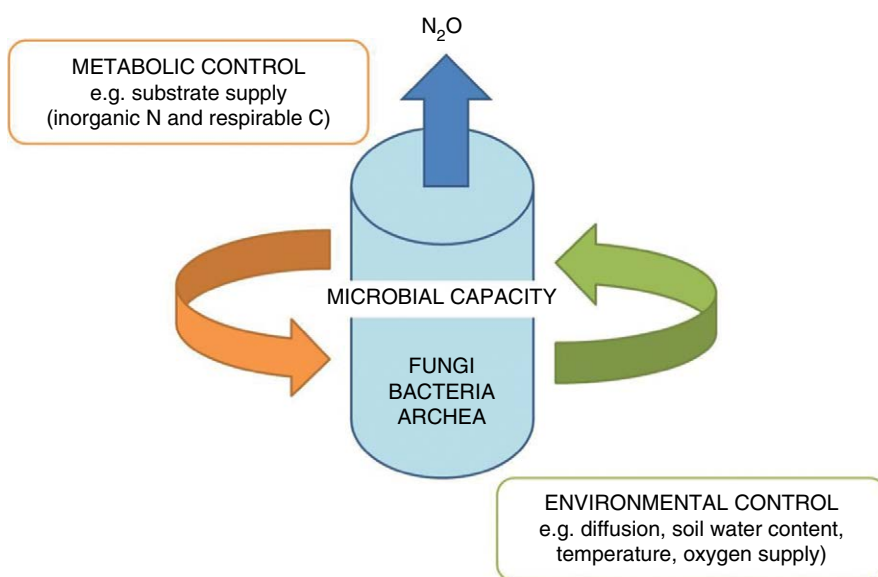


Fig. 3.1. Limiting factors on nitrous oxide (N_2O) production in the soil.

of organic carbon and nitrate (Bowden and Bormann, 1986). Nitrification (N oxidation pathways) may also prevail at WFPS values above 50%, while above 75% denitrification is the major pathway for N_2O production (Well *et al.*, 2006).

Nitrous Oxide Emissions from Legume-supported Cropping Systems

Monocrop legumes, legumes in rotation, legumes as intercrops and legumes grown as cover crop/green manures will all influence N_2O emissions from the soil through their input of biologically fixed N into the soil. In addition, root nodules may contribute directly to N_2O emissions via the inherent capacity of some rhizobial species/strains to reduce nitrite to nitrous oxide. In practice, the contribution of legume cropping to soil N_2O emissions may be divided into three separate processes:

- rhizobial denitrification within the nodules;
- nitrification and denitrification of biologically fixed N; and
- decomposition of N-rich residues to provide inorganic N.

Of these three processes, the addition of N-rich legume residues to soils is the most critical for peak N_2O emissions.

Rhizobial denitrification and N_2O production

The process of biological N fixation does not lead directly to N_2O emissions, but it has long been suspected that the enzyme responsible (nitrogenase) may contribute to some production of N_2O from reduction of nitrates present in root nodules. Isolated legume nodules and rhizobia bacteroids from a range of plant species have been shown to produce N_2O at limiting concentrations of oxygen and with nitrate as their source of nitrogen (Daniel *et al.*, 1980; O'Hara and Daniel, 1985; Coyne and Focht., 1987; Bedmar *et al.*, 2005; Monza *et al.*, 2006). Not all rhizobia share this property, indeed denitrification has been shown in only a few genera of N_2 -fixing bacteria and a majority of the species/strains studied lack a full complement of denitrification genes (Monza *et al.*, 2006).

Whatever the distribution and function of denitrification enzymes among symbiotic rhizobia, the extent of N_2O production from legume nodules in the field is not clear. Early work on upscaling laboratory rates of denitrification highlighted a considerable potential of N_2 -fixing bacteria to remove nitrate from agricultural soils. In the case of *Rhizobium lupini*, a measured bacterial density of 10^4 cells/g soil was calculated to give initial rates of denitrification of the order of 20 kg N removed/ha (O'Hara *et al.*, 1984), this loss of nitrogen being of a similar magnitude to field rates of N_2 fixation (O'Hara and Daniel, 1985). Despite such concerns, evidence for high rates of denitrification by legume nodules in the field is scarce (Zhong *et al.*, 2009). Given the considerable uncertainty in upscaling laboratory rates of N_2O flux by isolated nodules or symbiotic bacteria to the field, useful experiments would be those incorporating suitable controls to

compare N_2O flux from inoculated and non-inoculated plants. In the case of both pea and lentil, little difference in N_2O emissions has been determined between plants inoculated with strains of *Rhizobium leguminosarum* and control plants, and even between inoculated plants and soils planted with wheat (Zhong *et al.*, 2009). This suggests that N_2O emissions are not directly related to biological N_2 fixation by grain legumes, as further illustrated in soil box experiments incorporating wetting and drying cycles with pea and lentil crops and *R. leguminosarum* (Zhong *et al.*, 2011). Taking the lack of field-based data into consideration, N_2 fixation by legumes as a source of N_2O is no longer considered important by the Intergovernmental Panel on Climate Change (IPCC) and has been dropped from their emission calculation guidelines (Rochette and Janzen, 2005; IPCC, 2006).

Nitrification and denitrification of biologically fixed N

A comparison of N_2O emissions from different cropping systems by Muñoz *et al.* (2010) is summarized in Table 3.2 and highlights the range of N_2O emissions recorded.

Table 3.2. Nitrous oxide (N_2O) fluxes from different soil use and management. (From Muñoz *et al.*, 2010.)

System	Range N_2O flux (kg N_2O -N/ha/year)	Country	References
Cropping			
Continuous and rotation crops	0–44	Brazil, Canada, Denmark, New Zealand	Wagner-Riddle and Thurtell (1998), Gregorich <i>et al.</i> (2005), Metay <i>et al.</i> (2007), Sagggar <i>et al.</i> (2008), Chirinda <i>et al.</i> (2010), Allen <i>et al.</i> (2010)
Leguminous crop	0.3–4.7	Canada	Gregorich <i>et al.</i> (2005)
Rice	0–36	Australia, USA, Japan, China, Philippines, Indonesia, Taiwan, India	Majumdar (2009)
Shrub land/natural landscape	0–21	New Zealand, Finland	Malijanen <i>et al.</i> (2006), Sagggar <i>et al.</i> (2008)
Pasture			
Animal waste applied	0–156	Canada, New Zealand, England, the Netherlands, Japan, Canada, Denmark, USA	Gregorich <i>et al.</i> (2005), Sagggar <i>et al.</i> (2009)
Grazing	0.1–183	UK, New Zealand, Australia	Sagggar <i>et al.</i> (2008), Cardenas <i>et al.</i> (2010), Galbally <i>et al.</i> (2010), Matthews <i>et al.</i> (2010)

Pastures

Grazed grass/clover pastures have the largest recorded N_2O emissions with fixed nitrogen being released into the soil through both decay of leaf, stem and root litter and transfer to the soil N pool via faeces and urine from the grazing animals. Leaching of N and acidification of soils is a common problem here (Bouwman *et al.*, 2002), the drop in soil pH due to the acidifying effects of the nitrogenase reaction. This eventually leads to a decline in productivity of the grassland (Williams, 1980) hence liming of grasslands is a common solution (Galbally *et al.*, 2010). As N_2O emissions are reduced when soil pH values fall below pH 5.5, liming may lead directly to decreases in N_2O flux although field data on the effect of liming is scarce. Galbally *et al.* (2010) found no significant effect of liming on N_2O emissions from grazed legume pastures typical of Australia. Laboratory incubations of limed soils with urine added as a source of N also show little effect of raising the soil pH above 5.5 on N_2O emissions (Zaman *et al.*, 2007, 2008). Clover density may also be assumed to affect N_2O emissions in such systems through increasing N inputs into the soil but, as with the case of liming, few field data are available. A study of N_2O emissions from high- and low-density clover patches concluded that spatial heterogeneity in clover abundance may have very little impact on field-scale N_2O emissions in fertilized grasslands (Klumpp *et al.*, 2011).

Legume monocrops

These show the least emissions of N_2O in the published literature (Table 3.2) but care must be taken in interpretation of short-term studies. Nitrification and denitrification of biologically fixed N may represent a significant source of N_2O from agricultural systems in the long term where incorporation and mineralization of legume residues may lead to peaks in available nitrate. The majority of studies on legume monocrops are limited at best to 1 year and hence focus on the short term. Under these conditions with removal of a high proportion of biologically fixed N to the grain during growth and harvest, short-term measurements of N_2O emissions will fail to incorporate the effect of carryover of the remaining plant nitrogen in the soil (Evans *et al.*, 2001; Peoples *et al.*, 2001). Some authors consider the stubble of grain legumes to be a minor source of N_2O through mineralization given its low organic N content (Lemke *et al.*, 2007; Peoples *et al.*, 2009). For grass–clover stands or stands of forage legumes long-term dynamics of N loss are important. Carter and Ambus, (2006) found only 2% of the total N_2O -N emissions of biologically fixed N lost as N_2O in the short term, highlighting the importance of the long-term mineralization of plant material for N_2O emissions compared with recently fixed N. Accepting these limitations, Table 3.3 illustrates the mean and range of N_2O emissions as summarized by Jensen *et al.* (2011) and using additional data from the Legume Futures project, for a range of specific legume and non-legume crops. The apparent trend would be that grain legumes, forage legumes and grass–clover stands receiving minimal inorganic N fertilizer have lower emissions of N_2O than N-fertilized pastures and non-legume crops, but higher emissions than non-fertilized, non-legume crops (Rochette *et al.*, 2004; Jensen *et al.*, 2011).

In the case of legume systems showing higher N_2O emissions than non-legume crops grown with no added fertilizer, this would reflect N inputs provided by the

Table 3.3. Comparison of nitrous oxide (N₂O) emissions from legume and non-legume crops.

Crop	Total N ₂ O emissions per year or growing season (kg N ₂ O-N/ha)	
	Jensen <i>et al.</i> (2011)	Legume Futures project
Grassland		
N-fertilized pasture (grass)	4.5 (0.3–18.6)	
Mixed pasture sward (grass–clover)	0.5 (0.1–1.3)	
Pure legume stands		
Lucerne	2.0 (0.7–4.6)	0.6
White clover	0.8 (0.5–0.9)	
Galega		1.3 (1.1–1.4)
Grain legumes		
Faba bean	0.4	0.6 (0.02–1.5)
Field bean		0.08 (0.06–0.12)
Mung bean		0.4
Lupin	0.05	0.4
Lentil		0.06 (0.05–0.07)
Chickpea	0.06 (0.03–0.16)	
Field pea	0.7 (0.4–1.7)	1.0 (0.08–3.0)
Soybean	1.6 (0.3–7.1)	1.1 (0.9–1.2)
<i>Mean of all legumes</i>	1.3	0.6
N-fertilized crops		
Wheat	2.7 (0.09–1.6)	
Maize	2.7 (0.16–12.7)	
Canola	2.7 (0.13–8.6)	
<i>Mean N-fertilized crops</i>	3.2	
Soil (no legumes or fertilizer)	1.2 (0.03–4.8)	

legumes. As an example, Dick *et al.* (2006) in a comparison of soils from N-fixing and non-N-fixing trees found both higher N₂O emissions and pool of available N (NH₄⁺ and NO₃⁻) in the soil from those trees fixing N₂ from the atmosphere.

There are a few exceptions in the literature where very high emissions of N₂O have been recorded from legume monocrops, such as lucerne (alfalfa) (Rochette *et al.*, 2004) and soybean (Parkin and Caspar, 2006), but here the influence of previous land management and sources of N other than biologically fixed N must be considered.

Before inorganic N fertilizers, soil fertility in farms was typically managed using legume-rich pastures, cover crops or rotation. These management systems are seen by some as a means of increasing productivity in poorer areas of the globe and also to increase sustainable agricultural production (Crews and Peoples, 2004). For instance: (i) cereal–legume intercropping is a common crop production system in Africa; (ii) incorporation of groundnut into rice-based cropping systems increases productivity and income of smallholders in South-east Asia (Whitmore *et al.*, 2000); (iii) rotation of crops with fast-growing tree, shrub and herbaceous N₂-fixing legume species is widely adopted for soil fertility management in the

humid tropics (Millar *et al.*, 2004); and (iv) in southern Brazil the use of legume cover crops is increasingly common in no-tillage systems (Mielniczuk *et al.*, 2003).

Decomposition of N-rich residues to provide inorganic N

Both legume crops in rotation and their use as cover crops involve the incorporation of high-N plant residues into the soil. It is this aspect to legume systems, the incorporation of organic N into soils which following mineralization will provide sufficient substrate for nitrification and denitrification, which represents a significant source of N_2O . This may be further compounded by the higher N content and lower C:N ratios of legume tissues compared with other plant material.

In general, plant residues with high C:N ratios will immobilize soil N during initial microbial decomposition. In the short term, this has the effect of delaying the availability of inorganic nitrate for nitrification/denitrification but also for crop growth. In the long term though, plant-available N, yield and N uptake increase following straw addition with mineralization being extended (Cassman *et al.*, 1996; Eagle *et al.*, 2000). Inorganic N tends to be released from plant residues once excess C has been consumed by microbial growth. For legume residues this will occur rapidly due to both the high N content and the low C:N ratio of the tissue. A threshold C:N value of 20–25 has been proposed below which rapid N mineralization occurs (Frankenberger and Abdelmagid, 1985; Myers *et al.*, 1994).

The typical N content values for a variety of plant residues taken from data presented in Jensen *et al.* (2011) shows that C:N values vary from approximately 26:1 to 10:1 for legume tissues and from approximately 26:1 to 105:1 for non-leguminous tissues (Fig. 3.2). Both the high overall N content and low C:N ratios of legume residues will result in more rapid net N mineralization, providing an excess of mineral N with respect to microbial growth and increased substrate for the combined processes of nitrification and denitrification. In general, therefore, greater N_2O emissions are measured after incorporation of high-N plant residues (Baggs *et al.*, 2000; Millar *et al.*, 2004; Kaewpradit *et al.*, 2008; Gomes *et al.*, 2009; Frimpong *et al.*, 2011, 2012), with the peak in N_2O emissions occurring early after incorporation. Imbalances between the timing, availability and amount of newly mineralized N from legume residues and the onset of plant growth are therefore critical with respect to N_2O emissions, particularly if the legume is a cover crop and ploughed in as a green manure (Baggs *et al.*, 2000) or part of an improved ley ploughed over before cereal planting (Pu *et al.*, 1999).

To illustrate these points further, Table 3.4 provides a comparison of the percentage change effect on N_2O emissions of legumes grown in rotation versus legumes as green manure/cover crops. Accepting that few published studies provide suitable control values, the limited data available highlight the significant increase in N_2O flux possible where high N residues are incorporated into the soil. Irrespective of the scale of the percentage effect observed, the largest recorded flux values are comparable with those measured from crops fertilized with inorganic N. This comes in contrast to savings in both cost to the farmer in reducing fertilizer usage and environmental costs of reducing fertilizer manufacture, and further benefits of N carryover into the following crop.

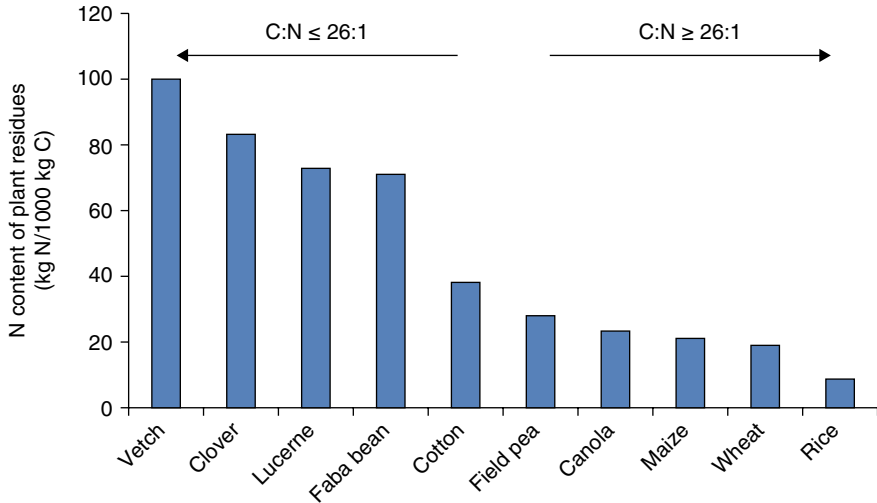


Fig. 3.2. N content and C:N ratios for legume and non-legume plant residues. (Adapted from Jensen *et al.*, 2011.)

Table 3.4. Effect of legume crop on N₂O emissions.

	Effect of legume crop on N ₂ O emissions compared with cereal crop/control (percentage change)	
	Legume crop in rotation (some residue incorporation) ^a	Legume crop as cover crop/green manure (significant residue incorporation) ^b
Mean	1.6	679
Minimum	-59	7.8
Median	-8	236
Maximum	113	1888

^aData from: MacKenzie *et al.* (1997), Dick *et al.* (2006), Drury *et al.* (2008), Halvorson *et al.* (2008), Guo *et al.* (2009) and Barton *et al.* (2013).

^bData from: Baggs *et al.* (2003), Millar *et al.* (2004), Kaewpradit *et al.* (2008), Gomes *et al.* (2009) and Frimpong *et al.* (2011).

Improving the synchrony between N availability and crop growth in these management systems would be critical in reducing N₂O flux and maybe N fertilized systems where top-dressings can match supply of N to demand are better than legume rotations in this respect (Cassman *et al.*, 2002; Crews and Peoples, 2004). One strategy that may prolong mineralization of legume residues through the season would be to manipulate the overall C:N ratio of the plant material applied. This may be achieved by mixing high-C cereal residues with high-N legume residues to allow for some measure of N immobilization (Myers *et al.*, 1994; Vinten *et al.*, 1998; Schwendener *et al.*, 2005; Kaewpradit *et al.*, 2008; Frimpong *et al.*, 2011).

Nitrate Leaching from Legume Crops

Leaching of nitrate from agricultural land is another important route of N loss from field soils reflecting both excess N in the soil comparative to crop growth requirements and the amount of water held by the soil immediately following N application (Addiscott and Powlson, 1992; Ledgard, 2001; Jensen and Hauggaard-Nielsen, 2003). In Europe, nitrate pollution of surface water and groundwater is a significant environmental problem with the annual nitrate concentration of approximately 30% of groundwaters exceeding the European Commission (EC) threshold value of 50 mg/l (Al-Kaisi and Licht, 2004; Hooker *et al.*, 2008). In legume-supported systems, particularly legume-rich pastures, leaching may be less of a problem than intensively managed systems (Owens *et al.*, 1994), although field data are lacking. Legume crops in rotation, or legume cover crops/green manures may still be associated with significant nitrate leaching from the soil due to both the lack of synchrony between N availability and crop growth and the amount of N provided through mineralization of the low C:N plant residues. As almost 75% of legume cover crop biomass is killed and left on the soil surface as a mulch which may be decomposed after 120 days, the potential for N leaching is high (Quemada *et al.*, 2004). Comparable field data on the effect of legume cropping on nitrate leaching is scarce in the literature. Beaudoin *et al.* (2005) observed the highest rates of nitrate leaching in crop rotations including pea for northern France due to the higher N content of plant biomass and lower N uptake rates from the soil, while one recent study on the use of legumes as cover crops in *Capsicum* production showed both high N leaching and a linear correlation between the N accumulated in the legume biomass and the total amount of nitrate leached (Campiglia *et al.*, 2011). Targeting the reduction of mineral N accumulation in soil, synchronizing N inputs with crop growth and crop N uptake and avoiding the buildup of excess N in soils would contribute towards decreased leaching (Mosier *et al.*, 2002) and one possible way to achieve this would be through intercropping of legumes with cereals, a form of low-N input agriculture popular in the tropics and now receiving interest in Europe.

Nitrogen and Phosphorus Losses from Intercropping of Legumes

Intercropping of legumes and cereals offers an opportunity to increase the input of fixed N into an agroecosystem both in the short term through direct N transfer (Patra *et al.*, 1986; Xiao *et al.*, 2004), and in the long term through mineralization of residues (Olesen *et al.*, 2002; Thorsted *et al.*, 2006). This may be achieved without compromising N uptake by the cereal crop or crop yield/stability (Hauggaard-Nielsen *et al.*, 2001), and in terms of economic yield may even prove beneficial (Willey, 1979; Hauggaard-Nielsen *et al.*, 2001). As intercropping involves both a reduction in applied inorganic N and, by virtue of the legume and non-legume plants growing in close proximity, a more efficient use of N, emissions of N₂O may be expected to be lower than for monocrops. However, as with N leaching,

there is a scarcity of information whereby direct comparisons between intercrops and monocrops can be made. Dyer *et al.* (2012) reported short-term N_2O emissions from a temperate maize–soybean intercropping system which was compared with monocropped maize and soybean. Emissions of N_2O were significantly lower from the intercrop treatments (11.5–12 $\mu\text{g } N_2O\text{-N m}^2/\text{h}$) than either the soybean or maize crops (13.5 $\mu\text{g } N_2O\text{-N m}^2/\text{h}$ and 14 $\mu\text{g } N_2O\text{-N m}^2/\text{h}$, respectively). Only one study has reported cumulative emissions for legume–cereal intercropping (Pappa *et al.*, 2011). This study included both barley–pea and barley–clover intercrops and also looked at varietal differences in N_2O emission and N leaching (Table 3.5). As the barley monocrop received no added N other than that provided from the previous grass crop, inclusion of the clover and pea (*cv.* Nitouche) crops increased annual N_2O emission by 211% and 267%, respectively. Of significant interest, however, was the observation that one of the second pea varieties (*cv.* Zero 4) reduced the annual N_2O emission by 22% and that unlike barley–clover, the barley–pea intercrops reduced nitrate leaching.

Intercropping may also have positive effects on plant phosphorus (P) uptake. Phosphorus is an essential plant nutrient but is a relatively immobile element in soils. Following adsorption by soil surfaces and organic matter it forms stable largely insoluble compounds that cannot be removed from soils by leaching or volatilization. Small amounts of phosphorus are, however, released into the soil solution in the form of phosphate ions and it is these that become available for plant uptake and potential loss through drainage.

In many Western countries, fertilizer phosphorus inputs over many years have led to the enrichment of soil with phosphorus in immobile pools. Utilization of this excess phosphorus can be improved by selecting rotational designs to include crops or intercrops that optimize phosphorus uptake (Edwards *et al.*, 2010). Brassicas have been shown to be particularly effective at mobilizing phosphorus from the soil, possibly as a consequence of their root exudates (Walker *et al.*, 2012). There is considerable evidence that the use of legume-based intercropping systems improves the efficiency of soil phosphorus utilization and it has been suggested that this may be also a consequence of mycorrhizal associations with the roots of legume species (Ren *et al.*, 2013). It is considered likely that legume roots are able to alter the pH of the soil and influence phosphorus availability accordingly (Betencourt *et al.*, 2012; Li *et al.*, 2013). Legume-supported

Table 3.5. N losses from spring barley–clover and barley–pea intercrops. (Adapted from Pappa *et al.*, 2011.)

Crop	N_2O flux (kg $N_2O\text{-N}/\text{ha}$)	Change compared with control (%)	Nitrate leached (kg $\text{NO}_3\text{-N}/\text{ha}$)	Change compared with control (%)
Barley	0.9		0.3	
Barley–clover	2.8	+ 211	1.3	+ 333
Barley–pea <i>cv.</i> Nitouche	3.3	+ 267	0.2	–33
Barley–pea <i>cv.</i> Zero 4	0.7	–22	0.1	–66

rotations (including intercrops) are of particular value in soils with lower phosphorus content or in circumstances where phosphorus is applied in insoluble forms. For example, organic farming regulations preclude the use of soluble phosphorus fertilizers, preferring instead to use composts or manure or other forms of phosphorus input such as rock phosphate. However, extreme phosphorus deficiency (often encountered in low pH soils) could possibly result in reduced growth of legumes in rotation as this becomes the next most limiting nutrient after nitrogen.

Conclusions

In terms of N loss from the soil via N_2O flux and NO_3^- leaching then available evidence indicates that the use of legumes as cover crops/green manure and surface mulches lead to high risks of losses of reactive nitrogen to the environment. Legumes in rotation, forage legumes and legumes as intercrops are more likely to be beneficial both in terms of reducing fertilizer inputs and in terms of cumulative N_2O emissions, but in the case of nitrification/denitrification, N_2O flux would be dependent on N inputs through mineralization of the previous crop.

Insufficient field data allows a definitive statement on N leaching and in terms of variable results from intercropping may reflect deeper rooting varieties (Pappa *et al.*, 2011). However, of the four cropping systems considered, the greatest potential for N loss would be the green manure/cover crop/mulch option.

Although legumes are known to mobilize phosphate pools, this comes at a cost of soil acidification that requires liming and may lead to some drainage losses.

Improvement of soil quality through soil structure and carbon sequestration would be pronounced both in long-term legume forage systems and in direct application of legume residues to soils as green manures/surface mulches.

References

- Addiscott, T.M. and Powlson, D.S. (1992) Partitioning losses of nitrogen fertilizer between leaching and denitrification. *Journal of Agricultural Science* 118, 101–107.
- Al-Kaisi, M. and Licht, M.A. (2004) Effect of strip tillage on corn nitrogen uptake and residual soil nitrate accumulation compared with no-tillage and chisel plough. *Agronomy Journal* 96, 1164–1171.
- Allen, D.E., Kingston, G., Rennenberg, H., Dalal, R.C. and Schmidt S. (2010) Effect of nitrogen fertilizer management and waterlogging on nitrous oxide emission from subtropical sugarcane soils. *Agriculture Ecosystems and Environment* 136, 209–217.
- Baggs, E.M., Rees, R.M., Smith, K.A. and Vinten, A.J.A. (2000) Nitrous oxide emissions from soils after incorporating crop residues. *Soil Use and Management* 16, 82–87.
- Baggs, E.M., Stevenson, M., Pihlatie, M., Regar, A., Cook, H. and Cadisch, G. (2003) Nitrous oxide emissions following application of residues and fertiliser under zero and conventional tillage. *Plant and Soil* 254, 361–370.
- Barton, L., Murphy, D.V. and Butterbach-Bahl, K. (2013) Influence of crop rotation and liming on greenhouse gas emissions from a semi-arid soil. *Agriculture, Ecosystems and Environment* 167, 23–32.

- Beaudoin, N., Saad, J.K., Van Laethem, C., Machet, J.M., Maucorps, J. and Mary, B. (2005) Nitrate leaching in intensive agriculture in Northern France: effect of farming practices, soils and crop rotations. *Agriculture, Ecosystems and Environment* 111, 292–310.
- Bedmar, E.J., Robles, E.F. and Delgado, M.J. (2005) The complete denitrification pathway of the symbiotic, nitrogen-fixing bacterium *Bradyrhizobium japonicum*. *Biochemical Society Transactions* 33, 145–148.
- Betencourt, E., Duputel, M., Colomb, B., Desclaux, D. and Hinsinger, P. (2012) Intercropping promotes the ability of durum wheat and chickpea to increase rhizosphere phosphorus availability in a low P soil. *Soil Biology & Biochemistry* 46, 181–190.
- Bouwman, A.F., Boumans, L.J.M. and Batjes, N.H. (2002) Emissions of N₂O and NO from fertilized fields: summary of available measurement data. *Global Biogeochemical Cycles* 16, 6–1.
- Bowden, W.B. and Bormann, F.H. (1986) Transport and loss of nitrous oxide in soil water after forest clear-cutting. *Science* 233, 867–869.
- Briggs, S.R., Cuttle, S., Goodlass, G., Hatch, D., King, J., Roderick, S. and Shepherd, M. (2005) Soil nitrogen building crops in organic farming – Defra research project OF0316 project publication. Department for Environment, Food and Rural Affairs (Defra), London.
- Bruinsma, J. (2003) *World Agriculture: Towards 2015/2030. An FAO Perspective*. Earthscan Publications Ltd, London.
- Campiglia, E., Mancinelli, R., Radicetti, E. and Marinari, S. (2011) Legume cover crops and mulches: effects on nitrate leaching and nitrogen input in a pepper crop (*Capsicum anuum* L.). *Nutrient Cycling in Agroecosystems* 89, 399–412.
- Cardenas, L.M., Thorman, R., Ashlee, N., Butler, M., Chadwick, D., Chambers, B., Cuttle, S., Donovan, N., Kingston, H., Lane, S., Dhanoa, M.S. and Scholefield, D. (2010) Quantifying annual N₂O emission fluxes from grazed grassland under a range of inorganic fertiliser nitrogen inputs. *Agriculture Ecosystems and Environment* 136, 218–226.
- Carter, M.S. and Ambus, P. (2006) Biologically fixed N₂ as a source for N₂O production in a grass-clover mixture as measured by ¹⁵N₂. *Nutrient Cycling in Agroecosystems* 74, 13–26.
- Cassman, K.G., de Datta, S.K., Amarante, S.T., Liboon, S.P., Samson, M.I. and Dizon, M.A. (1996) Long-term comparison of the agronomic efficiency and residual benefits of organic and inorganic nitrogen sources for tropical lowland rice. *Experimental Agriculture* 32, 427–444.
- Cassman, K.G., Dobermann, A.D. and Walters, D. (2002) Agroecosystems, nitrogen-use efficiency, and nitrogen management. *Ambio* 31, 132–140.
- Chirinda, N., Carter, M.S., Albert, K.R., Ambus, P., Olesen, J.E., Porter, J.R. and Petersen, S.O. (2010) Emissions of nitrous oxide from arable organic and conventional cropping systems on two soil types. *Agriculture Ecosystems and Environment* 136, 199–208.
- Coyne, M.S. and Focht, D.D. (1987) Nitrous oxide reduction in nodules: denitrification or N₂ fixation? *Applied Environmental Microbiology* 53, 1168.
- Crews, T.E. and Peoples, M.B. (2004) Legumes versus fertilizer sources of nitrogen: ecological tradeoffs and human needs. *Agriculture, Ecosystems and Environment* 102, 279–297.
- Daniel, R.M., Smith, I.M., Phillip, J.A.D., Ratcliffe, H.D., Drozd, J.W. and Bull, A.T. (1980) Anaerobic growth and denitrification by *Rhizobium japonicum* and other rhizobia. *Journal of General Microbiology* 120, 517–521.
- Davidson, E.A. (1991) Fluxes of nitrous oxide and nitric oxide from terrestrial ecosystems. In: Rogers, J.E. and Whitman, W.B. (eds) *Microbial Production and Consumption of Greenhouse Gases: Methane, Nitrogen Oxide and Halomethanes*. American Society for Microbiology, Washington, DC, pp. 219–235.
- Davidson, E.A., Keller, M., Erickson, H.E., Verchot, L.V. and Veldkamp, E. (2000) Testing a conceptual model of soil emissions of nitrous and nitric oxides. *Biosciences* 50, 667–680.
- Dick, J., Kaya, B., Soutora, M., Skiba, U., Smith, R., Niang, A. and Tabo, R. (2006) The contribution of agricultural practices to nitrous oxide emissions in semi-arid Mali. *Soil Use and Management* 24, 292–301.

- Ding, W.X., Cai, Y., Cai, Z.C., Yagi, K. and Zheng, X.H. (2007) Nitrous oxide emissions from an intensively cultivated maize–wheat rotation soil in the North China Plain. *Science of the Total Environment* 373, 501–511.
- Dobbie, K.E. and Smith, K.A. (2003) Nitrous oxide emission factors for agricultural soils in Great Britain: the impact of soil water-filled pore space and other controlling variables. *Global Change Biology* 9, 204–218.
- Drury, C.F., Yang, X.M., Reynolds, W.D. and McLaughlin, N.B. (2008) Nitrous oxide and carbon dioxide emissions from monoculture and rotational cropping of corn, soybean and winter wheat. *Canadian Journal of Soil Science* 88, 163–174.
- Dyer, L., Oelbermann, M. and Echarte, L. (2012) Soil carbon dioxide and nitrous oxide emissions during the growing season of maize–soybean intercropping and sole cropping systems. *Journal of Plant Nutrition and Soil Science* 175, 994–400.
- Eagle, A.J., Bird, J.A., Horwath, W.R., Linquist, B.A., Brouder, S.M., Hill, J.E. and van Kessel, C. (2000) Rice yield and nitrogen utilization efficiency under alternative straw management practices. *Agronomy Journal* 92, 1096–1103.
- Edenhofer, O., Pichs-Madruga, R.N., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S. and Eickemeier, P. (2014) Climate change 2014: Mitigation of climate change. Contribution of working group III to the fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge.
- Edwards, A.C., Walker, R.L., Maskell, P., Watson, C.A., Rees, R.M., Stockdale, E.A. and Knox, O.G.G. (2010) Improving bioavailability of phosphate rock for organic farming. In: Lichtfouse, E. (ed.) *Genetic Engineering, Biofertilisation, Soil Quality and Organic Farming*. Springer Science+Business Media BV, Dordrecht, the Netherlands.
- Evans, R.D., Rimer, R., Sperry, L. and Belnap, J. (2001) Exotic plant invasion alters nitrogen dynamics in an arid grassland. *Ecological Applications* 11, 1301–1310.
- Fixen, P.E. and West, F.B. (2002) Nitrogen fertilizers: meeting contemporary challenges. *AMBIO: A Journal of the Human Environment* 31, 169–176.
- Flessa, H., Russa, R., Schilling, R., Löffel, N., Munch, J.C., Kaiser, E.A. and Beese, F. (2002) N₂O and CH₄ fluxes in potato fields: automated measurement, management effects and temporal variation. *Geoderma* 105, 307–325.
- Flückiger, J., Blunier, T., Stauffer, B., Chappellaz, J., Spahni, R., Kawamura, K., Schwander, J., Stocker, T.F. and Dahl-Jensen, D. (2004) N₂O and CH₄ variations during the last glacial epoch: insight into global processes. *Global Biogeochemical Cycles* 18, doi:10.1029/2003GB002122.
- Fowler, D., Pilegaard, K., Sutton, M.A., Ambus, P., Raivonen, M., Duyzer, J., Simpson, D., Fagerli, H., Fuzzi, S., Schjoerring, J.K., Grainer, C., Neftel, A., Isaksen, I.S.A., Laj, P., Maione, M., Monks, P.S., Burkhardt, J., Daemmgen, U., Neiryneck, J., Personne, E., Wichink-Kruit, R., Butterbach-Bahl, K., Flechard, C., Tuovinen, J.P., Coyle, M., Gerosa, G., Loubet, B., Altimir, N., Gruenhage, L., Ammann, C., Cieslik, S., Paoletti, E., Mikkelsen, T.N., Ro-Poulsen, H., Cellier, P., Cape, J.N., Horvath, L., Loreto, F., Niinemets, U., Palmer, P.I., Rinne, J., Misztal, P., Nemitz, E., Nilsson, D., Pryor, S., Gallagher, M.W., Vesala, T., Skiba, U., Brüeggemann, N., Zechmeister-Boltenstern, S., Williams, J., O'Dowd, C., Facchini, M.C., de Leeuw, G., Flossman, A., Chaumerliac, N. and Erisman, J.W. (2009) Atmospheric composition change: ecosystems–atmosphere interactions. *Atmospheric Environment* 43, 5193–5267.
- Frankenberger, W.T. and Abdelmagid, H.M. (1985) Kinetic parameters of nitrogen mineralisation rate of leguminous crops incorporated into soil. *Plant and Soil* 87, 257–271.
- Frimpong, K.A., Yawson, D.O., Baggs, E.M. and Agyarko, K. (2011) Does incorporation of cowpea–maize residue mixes influence nitrous oxide emission and mineral nitrogen release in a tropical luvisol? *Nutrient Cycling in Agroecosystems* 91, 281–292.
- Frimpong, K.A., Yawson, D.O., Agyarko, K. and Baggs, E.M. (2012) N₂O emission and mineral N release in a tropical acrisol incorporated with mixed cowpea and maize residues. *Agronomy* 2, 167–186.

- Galbally, I.E., Meyer, M.C.P., Wang, Y.-P., Smith, C.J. and Weeks, I.A. (2010) Nitrous oxide emissions from a legume pasture and the influences of liming and urine addition. *Agriculture, Ecosystems and Environment* 136, 262–272.
- Gomes, J., Bayer, C., de Sousa Costa, F., de Cássia Piccolo, M., Zanatta, J.A., Vieira, F.C.B. and Six, J. (2009) Soil nitrous oxide emissions in long-term cover crops-based rotations under subtropical climate. *Soil and Tillage Research* 106, 36–44.
- Gregorich, E.G., Rochette, P., Vandenbygaart, A.J. and Angers, D.A. (2005) Greenhouse gas contributions of agricultural soils and potential mitigation practices in Eastern Canada. *Soil and Tillage Research* 83, 53–72.
- Guo, Z.L., Cai, C.F., Li, Z.X., Wang, T.W. and Zheng, M.J. (2009) Crop residue effect on crop performance, soil N₂O and CO₂ emissions in alley cropping systems in subtropical China. *Agroforestry Systems* 76, 67–80.
- Halvorson, A.D., Del Grosso, S.J. and Reule, C.A. (2008) Nitrogen, tillage and crop rotation effects on nitrous oxide emissions from irrigated systems. *Journal of Environmental Quality* 37, 1337–1344.
- Hauggaard-Nielsen, H., Ambus, P. and Jensen, E.S. (2001) Temporal and spatial distribution of roots and competition for nitrogen in pea–barley intercrops – a field study employing 32P technique. *Plant and Soil* 236, 63–74.
- Hooker, K.V., Coxon, C.E., Hackett, R., Kirwan, L.E., O’Keefe, E. and Richards, K.G. (2008) Evaluation of cover crop and reduced cultivation for reducing nitrate leaching in Ireland. *Journal of Environmental Quality* 37, 138–145.
- Intergovernmental Panel on Climate Change (IPCC) (2006) 2006 IPCC guidelines for national greenhouse gas inventories. In: Eggleston, H.S., Buendia, L., Miwa, K., Ngara, T. and Tanabe, K. (eds) *Agriculture, Forestry and Other Land Use*. Prepared by the National Greenhouse Gas Inventories Programme, Vol. 4. Institute for Global Environmental Strategies (IGES), Japan.
- Intergovernmental Panel on Climate Change (IPCC) (2007) Climate change 2007: The scientific basis. Contribution of working group 1 to the fourth assessment report of the IPCC. Cambridge University Press, Cambridge.
- Jensen, E.S. and Hauggaard-Nielsen, H. (2003) How can increased use of biological N₂ fixation in agriculture benefit the environment? *Plant and Soil* 252, 177–186.
- Jensen, E.S., Peoples, M., Boddey, R.M., Gresshoff, P.M., Hauggaard-Nielsen, H., Alves, B.J.R. and Morrison, M.J. (2011) Legumes for the mitigation of climate change and the provision of feedstock for biofuels and biorefineries. A review. *Agronomy for Sustainable Development* 32, 329–364.
- Kaewpradit, W., Toomsan, B., Vityakon, P., Limpinuntana, V., Saenjan, P., Jogloy, S., Patanothai, A. and Cadisch, J. (2008) Regulating mineral N release and greenhouse gas emissions by mixing groundnut residues and rice straw under field conditions. *European Journal of Soil Science* 59, 640–652.
- Khalil, M.K., Rosenani, A.R., Van Cleemput, O.V.C., Boeckx, P.B., Shamshuddin, J.S. and Fauziah, C.F. (2002) Nitrous oxide production from an ultisol of the humid tropics treated with different nitrogen sources and moisture regimes. *Biology and Fertility of Soils* 36, 59–65.
- Klumpp, K., Bloor, J.M.G., Ambus, P. and Soussana, J.-F. (2011) Effects of clover density on N₂O emissions and plant–soil N transfers in a fertilised upland pasture. *Plant and Soil* 343, 97–107.
- Kroeze, C. (1999) Closing the global N₂O budget: a retrospective analysis 1500–1994. *Global Biogeochemical Cycles* 13, 1–8.
- Ledgard, S.F. (2001) Nitrogen cycling in low input legume-based agriculture, with emphasis on legume/grass pastures. *Plant and Soil* 228, 43–59.
- Lemke, R.L., Zhong, Z., Campbell, C.A. and Zentner, R. (2007) Can pulse crops play a role in 580 mitigating greenhouse gases from North American agriculture? *Agronomy Journal* 99, 1719–1725.

- Li, X.P., Mu, Y.H., Cheng, Y.B., Liu, X.G. and Nian, H. (2013) Effects of intercropping sugarcane and soybean on growth, rhizosphere soil microbes, nitrogen and phosphorus availability. *Acta Physiologiae Plantarum* 35, 1113–1119.
- MacKenzie, A.F., Fan, M.X. and Cadrin, F. (1997) Nitrous oxide emissions as affected by tillage, corn–soybean–alfalfa rotations and nitrogen fertilization. *Canadian Journal of Soil Science* 77, 145–152.
- Majumdar, D. (2009) Past, present and future of nitrous oxide emissions from rice field: a treatise. In: Sheldon, A.I. and Barnhart, E.P. (eds) *Nitrous Oxide Emissions Research Progress*. Environmental Science, Engineering and Technology Series. Nova Science Publishers, New York, pp. 179–252.
- Malhi, S.S., Lemke, R., Wang, Z.H. and Chhabra, B.S. (2006) Tillage, nitrogen and crop residue effects on crop yield, nutrient uptake, soil quality and greenhouse gas emissions. *Soil and Tillage Research* 90, 171–183.
- Malijanen, M., Nykänen, H., Moilanen, M. and Martikainen, P.J. (2006) Greenhouse gas fluxes of coniferous forest floors as affected by wood ash addition. *Forest Ecology and Management* 237, 143–149.
- Matthews, R.A., Chadwick, D.R., Retter, A.L., Blackwell, M.S.A. and Yamulki, S. (2010) Nitrous oxide emissions from small scale farmland features of UK livestock farming systems. *Agriculture Ecosystems and Environment* 136, 192–198.
- Metay, A., Oliver, R., Scopel, E., Douzet, J.M., Alves Moreira, J.A., Maraux, F., Feigl, B.J. and Feller, C. (2007) N₂O and CH₄ emissions from soils under conventional and no-till management practices in Goiania (Cerrados, Brazil). *Geoderma* 141, 78–88.
- Mielniczuk, J., Bayer, C., Vezzani, F.M., Lovato, T., Fernandes, F.F. and Debarba, L. (2003) Manejo de solo e culturas e sua relação com os estoques de carbono e nitrogênio do solo. *Tópicos em ciência do solo* 3, 209–248.
- Millar, N., Ndufa, J.K., Cadisch, G. and Baggs, E.M. (2004) Nitrous oxide emissions following incorporation of improved–fallow residues in the humid tropics. *Global Biogeochemical Cycles* 18, doi: 10.1029/2003GB002114.
- Monza, J., Irisarri, P., Díaz, P., Delgado, M.J., Mesa, S. and Bedmar, E.J. (2006) Denitrification ability of rhizobial strains isolated from *Lotus* sp. *Antonie Van Leeuwenhoek, International Journal of General and Molecular Microbiology* 89, 479–484.
- Mosier, A.R., Bleken, M.A., Chaiwanakupt, P., Ellis, E.C., Frenzy, J.R., Howarth, R.B., Matson, P.A., Minami, K., Naylor, R., Weeks, K.N. and Zhu, Z.-L. (2002) Policy implications of human-accelerated nitrogen cycling. *Biogeochemistry* 57, 477–516.
- Muñoz, C., Paulino, L., Monreal, C. and Zagal, E. (2010) Greenhouse gas (CO₂ and N₂O) emissions from soils: a review. *Chilean Journal of Agricultural Research* 70, 485–497.
- Myers, R.J.K., Palm, C.A., Cuevas, E., Gunatilleke, I.U.N. and Brossard, M. (1994) The synchronisation of nutrient mineralisation and plant nutrient demand. In: Woomer, P.I. and Swift, M.J. (eds) *The Biological Management of Tropical Soil Fertility*. Wiley, Chichester, UK, pp. 81–116.
- O'Hara, G. and Daniel, R.M. (1985) Rhizobial denitrification: a review. *Soil Biology and Biochemistry* 17, 1–9.
- O'Hara, G.W., Daniel, R.M., Steele, K.W. and Bonish, P.M. (1984) Nitrogen losses from soils caused by *Rhizobium*-dependent denitrification. *Soil Biology and Biochemistry* 16, 429–431.
- Olesen, J.E., Rasmussen, I.A., Askegaard, M. and Kristensen, K. (2002) Whole-rotation dry matter and nitrogen grain yields from the first course of an organic farming crop rotation experiment. *Journal of Agricultural Science* 139, 361–370.
- Owens, L.B., Edwards, W.M. and Van Keuren, R.W. (1994) Groundwater nitrate levels under fertilized grass and grass legume pastures. *Journal of Environmental Quality* 23, 752–758.

- Pappa, V.A., Rees, R.M., Walker, R.L., Baddeley, J.A. and Watson, C.A. (2011) Nitrous oxide emissions and nitrate leaching in an arable rotation resulting from the presence of an intercrop. *Agriculture, Ecosystems and Environment* 141, 153–161.
- Parkin, T.B. and Kaspar, T.C. (2006) Nitrous oxide emissions from corn–soybean systems in the Midwest. *Journal of Environmental Quality* 35, 1496–1506.
- Patra, D.D., Sachdev, M.S. and Subbiah, B.V. (1986) ¹⁵N studies on the transfer of legume-fixed nitrogen to associated cereals in intercropping systems. *Biology and Fertility of Soils* 2, 165–171.
- Peoples, M.B., Bowman, A.M., Gault, R.R., Herridge, D.F., McCallum, M.H., McCormick, K.M., Norton, R.M., Rochester, I.J., Scammell, G.J. and Schwenke, G.D. (2001) Factors regulating the contributions of fixed nitrogen by pasture and crop legumes to different farming systems of eastern Australia. *Plant and Soil* 228, 29–41.
- Peoples, M.B., Brockwell, J., Herridge, D.F., Rochester, I.J., Alves, B.J.R., Urquiaga, S., Boddey, R.M., Dakora, F.D., Bhattarai, S., Maskey, S.L., Sampet, C., Rerkasem, B., Khan, D.F., Hauggard-Nielsen, H. and Jensen, E.S. (2009) The contributions of nitrogen-fixing crop legumes to the productivity of agricultural systems. *Symbiosis* 48, 1–17.
- Prather, M.J., Ehhalt, D., Dentener, F.J., Derwent, R., Dlugokencky, E.J., Holland, E.A., Isaksen, I., Katima, J., Kirchhoff, V., Matson, P.A., Midgley, P., Wang, M. and Al, E. (2001) Atmospheric chemistry and greenhouse gases. In: Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., Van der Linden, P.J., Dai, X., Maskell, K. and Johnson, C.A. (eds) *Climate Change 2001: The Scientific Basis*. Cambridge University Press, Cambridge.
- Pu, G., Saffigna, P.G. and Strong, W.M. (1999) Potential for denitrification in cereal soils of northern Australia after legume or grass–legume pastures. *Soil Biology and Biochemistry* 31, 667–675.
- Quemada, M. and Cabrera, M.L. (2004) Predicting crop residue decomposition using moisture adjusted time scales. *Nutrient Cycling in Agroecosystems* 70, 283–291.
- Ren, L.X., Lou, Y.S., Zhang, N., Zhu, X.D., Hao, W.Y., Sun, S.B., Shen, Q.R. and Xu, G.H. (2013) Role of arbuscular mycorrhizal network in carbon and phosphorus transfer between plants. *Biology and Fertility of Soils* 49, 3–11.
- Rochette, P. and Janzen, H.H. (2005) Towards a revised coefficient for estimating N₂O emissions from legumes. *Nutrient Cycling in Agroecosystems* 73, 171–179.
- Rochette, P., Angers, D.A., Bélanger, G., Chantigny, M.H., Prevost, D. and Levesque, G. (2004) Emissions of N₂O from alfalfa and soybean crops in eastern Canada. *Soil Science Society of America Journal* 68, 93–506.
- Saggar, S., Tate, K.R., Giltrap, D.L. and Singh, J. (2008) Soil–atmosphere exchange of nitrous oxide and methane in New Zealand terrestrial ecosystems and their mitigation options: a review. *Plant and Soil* 309, 25–42.
- Saggar, S., Luo, J., Giltrap, D. and Maddena, M. (2009) Nitrous oxide emissions from temperate grasslands: processes, measurements, modelling and mitigation. In: Sheldon, A.I. and Barnhart, E.P. (eds) *Nitrous Oxide Emissions Research Progress*. Environmental Science and Technology Series. Nova Science Publishers, New York, pp. 1–66.
- Schwendener, C.M., Lehmann, J., de Camargo, P.B., Luizão, R.C.C. and Fernandes, E.C.M. (2005) Nitrogen transfer between high- and low-quality leaves on a nutrient-poor oxisol determined by ¹⁵N enrichment. *Soil Biology and Biochemistry* 37, 787–794.
- Šimek, M. and Cooper, J.E. (2002) The influence of soil pH on denitrification: progress towards the understanding of this interaction over the last 50 years. *European Journal of Soil Science* 53, 345–354.
- Smil, V. (1999) Nitrogen in crop production: an account of global flows. *Global Biogeochemical Cycles* 13, 647–662.
- Smith, K. (1997) The potential for feedback effects induced by global warming on emissions of nitrous oxide by soils. *Global Change Biology*, 3, 327–338.

- Smith, K.A., Ball, T., Conen, F., Dobbie, K.E., Massheder, J. and Rey, A. (2003) Exchange of greenhouse gases between soil and atmosphere: interactions of soil physical factors and biological processes. *European Journal of Soil Science* 54, 779–791.
- Smith, P., Martino, D., Cai, C., Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle, S., O'Mara, F., Rice, C., Scholes, B. and Sirotenko, O. (2007) Agriculture. In: Metz, B., Davidson, O.R., Bosch, P.R., Dave, R. and Meyer, L.A. (eds) *Climate change 2007, mitigation. Contribution of working group 11 to the fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC)*. Cambridge University Press, Cambridge.
- Sowers, T. (2001) N₂O record spanning the penultimate deglaciation from the Vostok ice core. *Journal of Geophysical Research–Atmospheres* 106, 31903–31914.
- Thorsted, M.D., Olesen, J.E. and Weiner, J. (2006) Width of clover strips and wheat rows influence grain yield in winter wheat/white clover intercropping. *Field Crops Research* 95, 280–290.
- Vinten, A.J.A., Davis, R., Castle, K. and Baggs, E.M. (1998) Control of nitrate leaching from a nitrate vulnerable zone using paper mill waste. *Soil Use Management* 14, 44–51.
- Wagner-Riddle, C. and Thurtell, G.W. (1998) Nitrous oxide emission from agricultural fields during winter and spring thaw as affected by management practices. *Nutrient Cycling in Agroecosystems* 52, 151–163.
- Walker, R.L., Edwards, A.C., Maskell, P., Watson, C.A., Rees, R.M., Knox, O.G.G. and Stockdale, E.A. (2012) The effect of co-composted cabbage and ground phosphate rock on the early growth and P uptake of oilseed rape and perennial ryegrass. *Journal of Plant Nutrition and Soil Science* 175, 595–603.
- Well, R., Kurganova, I., Lopes de Gerenyu, V. and Flessa, H. (2006) Isotopomer signatures of soil-emitted N₂O under different moisture conditions, microcosm study with arable loess soil. *Soil Biology and Biochemistry* 38, 2923–2933.
- Whitmore, A.P., Cadisch, G., Toomsan, B., Limpinuntana, V., van Noorwijk, M. and Purnomosidhi, P. (2000) An analysis of the economic values of novel cropping systems in N.E. Thailand and S. Sumatra. *Netherlands Journal of Agricultural Science* 48, 1055–1114.
- Willey, R.W. (1979) Intercropping: its importance and research needs. Competition and yield advantages. *Field Crop Abstracts* 1, 1–10.
- Williams, C.H. (1980) Soil acidification under clover pasture. *Australian Journal of Experimental Agriculture* 20, 561–567.
- Xiao, Y., Li, L. and Zhang, F. (2004) Effect of root contact on interspecific competition and N transfer between wheat and faba bean using direct and indirect ¹⁵N techniques. *Plant and Soil* 262, 45–54.
- Zaman, M., Nguyen, M.L., Matheson, F., Blennerhassett, J.D. and Quin, B.F. (2007) Can soil amendments (zeolite or lime) shift the balance between nitrous oxide and dinitrogen emissions from pasture and wetland soils receiving urine or urea-N? *Australian Journal of Soil Research* 45, 543–553.
- Zaman, M., Nguyen, M.L. and Sagar, S. (2008) N₂O and N₂ emissions from pasture and wetland soils with and without amendments of nitrate, lime and zeolite under laboratory condition. *Australian Journal of Soil Research* 46, 526–534.
- Zhong, Z., Lemke, R.L. and Nelson, L.M. (2009) Nitrous oxide emissions associated with nitrogen fixation by grain legumes. *Soil Biology and Biochemistry* 41, 2283–2291.
- Zhong, Z., Nelson, L.M. and Lemke, R.L. (2011) Nitrous oxide emissions from grain legumes as affected by wetting/drying cycles and crop residues. *Biology and Fertility of Soils* 47, 687–699.

4

Legume Crops and Biodiversity

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Abstract

Modern intensive cropping systems rely on simple cropping sequences, mineral fertilizers and chemical crop protection. This has led to a reduction of crop diversity, simplified landscapes and declines in biodiversity. However, even today in intensive farming systems, legume-supported cropping has the potential to deliver many ecosystem services, both directly due to unique trait combinations and indirectly via promoting biodiversity and by facilitating services such as pollination, pest control and soil improvement. This chapter outlines the effects of legume cropping on biodiversity, focusing on legume-specific traits and their interactions with agricultural management. Legumes have complex direct and indirect interactions with the surrounding agroecosystem and its management, so it is not possible to fully separate general crop management effects from effects of management that is specific to legume crops, and legume-trait effects. Legumes can benefit farmland biodiversity when included in highly productive cropping systems. Legume crops qualify for the ecological focus areas in 'greening' of the Common Agricultural Policy (CAP) of the European Union (EU). Several of the effects of legumes are related to changes in management practices, such as a reduced use of pesticides, fertilizer or soil tillage. Of course benefits for biodiversity may be also partially achieved by other crops and diversified crop rotations. However, legume traits and management practices vary at a species or even cultivar level and so here we provide a general overview of the effects on biodiversity.

Introduction

Agroecosystems are characterized by more frequent disturbance of vegetation than occurs in most natural and semi-natural ecosystems. Crops are communities of plants that are simplified by weed control and fertilization (Tilman *et al.*, 2002). Additionally, agricultural management affects many non-crop species via

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addition (fertilization) or removal of organic material (harvest), regular soil disturbance (tillage, compaction), and the use of crop protection products. This reduces the ability of ecosystems to provide goods and services (Tilman *et al.*, 2002). The use of legumes to diversify cropping systems and simultaneously support species conservation and food security requires an understanding of the underlying mechanisms that generate and maintain diverse and productive agroecosystems. As dicotyledonous, mass-flowering and nitrogen-fixing plants, many legume species are different from non-leguminous mass-flowering crops such as oilseed rape (*Brassica napus* ssp. *napus*) or sunflower (*Helianthus annuus*). Grain legumes (e.g. soybean, *Glycine max* Merr) or faba bean (*Vicia faba*) and forage legumes (e.g. lucerne (alfalfa), *Medicago sativa*; and clovers, *Trifolium* spp.), as 'catch', 'cover', 'green manure' or 'alternative host' intercrops vary in their characteristics and accordingly in their impact on the agroecosystem and surrounding landscapes. Yet to harness potentially positive effects, the agricultural management as well as the trait combination and expression of the specific legume crop must be considered (Fig. 4.1).

How Legume Traits Influence Local Biodiversity on Farmed Land

Research into effects on biodiversity has focused predominantly on natural or semi-natural ecosystems. In farmed ecosystems, biodiversity is vital for the supply of supporting and regulatory ecosystem services, including pollination, nutrient cycling, soil structure and functioning, hydrological processes and crop protection (Tscharntke *et al.*, 2005; Altieri and Rogé, 2010) if provisioning services (crop production) are to be maximized (Tscharntke *et al.*, 2005; Altieri and Rogé,

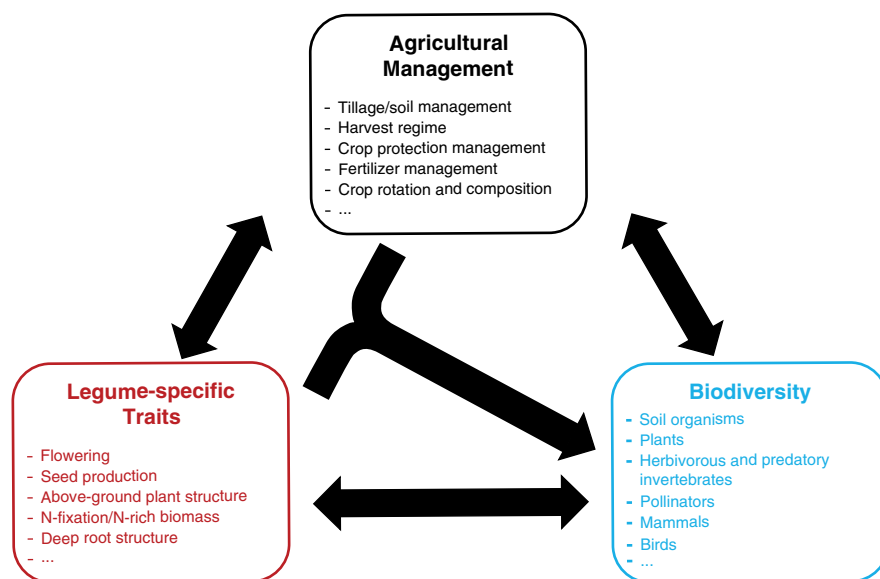


Fig. 4.1. Potential effects and interactions between legume traits, agricultural management and biodiversity in legume-supported cropping.

2010). In both natural and farmed systems, several legume traits, such as mass-flowering, biological nitrogen fixation (BNF), weed suppression, niche generation or soil improvement often act in combination to affect biodiversity. However, for an understanding of the effects of legumes on biodiversity, it is useful to consider these traits separately, also because they differ between legume species in their combination and expression.

Flowering and pollination

The characteristic floral morphology of most legumes, comprising a long corolla, curved nectar tube and bright colour is widely considered to have contributed to the rapid divergence of this plant group and co-evolution with specific pollinators (Leppik, 1966) (Fig. 4.2). As a result, flower-feeding insects of the order Hymenoptera, whose proboscis and feeding strategies have evolved in tandem with the pollination requirements of legume flowers, benefit from legume-rich grass and forage systems. Studies have shown that the floral abundance, species richness and the availability of nectar and pollen, especially in the form of legumes, can drive bumblebee community composition and can enhance pollinator populations (Potts *et al.*, 2009).

Pollinator decline has been driven in part by habitat loss, reducing the abundance and diversity of floral resources and nesting opportunities (Goulson *et al.*, 2015). In addition, pollinators have been exposed to cocktails of agrochemicals and other changes in agricultural practices (Goulson *et al.*, 2015). As a consequence of declines in pollinator abundance and diversity, seed yields can decline, for example, in red clover (*Trifolium pratense*) (Bommarco *et al.*, 2012). To conserve and promote bees and local pollination services, field margins sown with the legume-based pollen and nectar mixture have been shown to be beneficial in terms of attracting bees (Carvell *et al.*, 2007; Woodcock *et al.*, 2014), although legume flowers are not a suitable resource for many non-bee pollinators. Therefore, planting legumes could enhance bee populations in some contexts (Scheper *et al.*, 2013), aid conservation efforts and simultaneously improve crop yields (Palmer *et al.*, 2009). Additionally, many legumes provide extra-floral nectar, which is accessible to many invertebrates, including beneficial species such as parasitoid wasps (Géneau *et al.*, 2012). Not all legumes depend on bee-mediated pollination or



Fig. 4.2. Honeybee (*Apis mellifera*) foraging on lucerne (*Medicago sativa* subsp. *varia*). (Photo credit: Christine Venjakob.)

provide sufficient amounts of accessible nectar and pollen to be visited by foraging bees (e.g. pea, *Pisum sativum*; or lentil, *Lens culinaris*) (see Chapter 5, this volume), or produce resources throughout the season. Thus a positive effect of legumes on pollinator abundance and diversity depends on the legume species and whether its rewards can be utilized by a particular species or not (Palmer *et al.*, 2009; Mader and Hopwood, 2013). On a broader scale, this may also influence the pollination of other flowering plants, including other crops, either by facilitating pollination in other species by attracting additional pollinators, or by competing for pollinators (Brookes *et al.*, 1994; Ghazoul, 2006).

There are calls for altering crop breeding targets to improve additional environmental functions and support better integration of crops into healthy agroecosystems (Palmer *et al.*, 2009). Selection for traits to improve floral attractiveness, including colour, morphology, phenology and the quantity and quality of nectar and pollen rewards for pollinators is an area in which crop breeding strategies could make gains while simultaneously improving crop productivity through increased cross-pollination and hybridization (Palmer *et al.*, 2009). Self-pollination has been promoted in many grain legumes such as soybean during their domestication (Mader and Hopwood, 2013). However, out-breeding remains the dominant mode for the majority of forage legumes and other species not predominantly bred for seed production (Carbonero *et al.*, 2011).

Biological nitrogen fixation

The nitrogen (N)-rich root, shoot and leaf biomass of legume crops, enabled by BNF, increases the availability of N to neighbouring or succeeding non-legume crop plants (Kumar *et al.*, 1999). Decomposer communities, microorganisms, dependent fauna and herbivores play an important role in recycling plant litter and making the fixed N available to surrounding plants. For example, the N transfer from clover to wheat is related to earthworm activity (Schmidt and Curry, 1999). Root exudates as well as living and senescent root biomass provide additional below-ground N-enriched input to the soil (Sugiyama and Yazaki, 2012). Through subsequent trophic interactions, these N-rich resources are transferred throughout the food web. This may increase plant density and unsown vegetation biodiversity, although this may not be the case in highly fertile managed agricultural grasslands where nitrogen is not a limiting nutrient (Tilman *et al.*, 1997).

The low C:N ratio of legume biomass can also influence higher trophic levels by providing high-quality, accessible nutrients (Sileshi and Mafongoya, 2007). This is available to all invertebrate herbivores, so it benefits pest species as well as those with neutral or positive impacts on crop productivity. Thus without a diverse and well-structured community of invertebrates and other organisms on farms, the attractiveness of legumes could have a detrimental effect on production in cropping systems by attracting herbivores that may spill over into both legume and non-legume crops and become pests. In a healthy ecosystem, increased pest populations also lead to increased predator and parasitoid populations, supporting equilibrium between pests and natural enemies (Price *et al.*, 1980).

Increased diversity and other changes to the non-crop vegetation and invertebrate community, resulting not only from legume cropping, can also benefit farmland bird populations by promoting species upon which their diets rely (Moorcroft *et al.*, 2002).

N-rich legume plant material used as a green manure crop or present as litter increases the activity and abundance of soil fauna such as *Enchytraeidae* (Lagerlof *et al.*, 1989) as well as decomposition by soil microbes (Sileshi *et al.*, 2008). The presence and quality of the litter (below and above ground) increases the abundance of earthworms, as van Eekeren *et al.* (2009) showed in a comparative study of white clover (*Trifolium repens*) and ryegrass (*Lolium perenne*). Soil invertebrates, including earthworms and centipedes, were found to benefit from incorporating legume material pruned from leguminous trees into the ground in maize cropping agroforestry systems (Sileshi *et al.*, 2008) indicating that such added nutrients may benefit decomposer groups and the soil food web.

Above-ground plant structure of legumes

Legumes compete with non-crop species in a way that contrasts with monocotyledonous crops such as cereals or maize. This leads to weed communities that are different to those in monocotyledonous crops (Meiss *et al.*, 2010c). Climbing and creeping growth forms add further structural complexity, which is of particular relevance in intercropped and undersown systems that have a high leaf area index (Bilalis *et al.*, 2010). Thus, where legumes are strong competitors, such as the fast-growing and creeping white clover (*T. repens*) within green mulches, intercropping and undersowing can reduce non-crop vegetation preventing invasion of swards by otherwise competitive weeds (Frankow-Lindberg *et al.*, 2009). Legume-based cover and green manure crops may alter the community structure of associated vegetation in favour of broadleaved species leading to the maintenance of a more diverse community featuring a greater range of rare plant species (Meiss *et al.*, 2010c).

The regrowth of a perennial legume such as lucerne or clover allows several harvests/cutting cycles per year and creates longer ground cover. The cutting regime has a strong influence on floral and faunal composition and diversity (Everwand *et al.*, 2014). In grassland systems with legumes the balance between cutting and grazing can also influence the persistence of legumes within the sward. Grazing maintains legume cover more effectively than cutting (Woodcock *et al.*, 2014). The presence of perennial grass or grass–legume leys in rotation affects the weed flora (Meiss *et al.*, 2010b) and can reduce the risk of noxious annual weeds (see Chapter 11, this volume).

Root characteristics and morphology

Legume-supported systems impact on vegetation communities via changes to soil structure, seed bank and soil chemistry over the course of several cropping cycles. Many legumes have deep roots, high mycorrhization and high abundances of both symbiotic and non-symbiotic N-fixing bacteria in comparison to cereals.

Those root and rhizosphere characteristics improve soil structure (Mytton *et al.*, 1993; Lupwayi and Kennedy, 2007). However, root characteristics differ between legume species. The taproot of faba bean (*V. faba*) for instance is larger and more robust than that of other cool-season legumes (see Chapter 5, this volume). The roots of lucerne can grow deeper than 2 m, and transport assimilates down as well as nutrients up through the soil profile (see Chapter 11, this volume). Additionally, lucerne roots release allelopathic compounds, some of which directly limit the growth of weed flora in the later stages of a crop rotation (Xuan and Tsuzuki, 2002) or suppress root damage by pathogenic nematodes and enhance interspecific biocontrol within the nematofauna, as shown for the legume species *Mucuna pruriens* var. *utilis* (Blanchart *et al.*, 2006). This reduces the need for pesticide input and weed control measures. For example, lucerne is used as a 'biological break' in a rotation to reduce soil pest populations that may build up over successive seasons of other arable crops (Altieri, 1999).

How Management of Legume-supported Cropping Affects Biodiversity

Crops are managed to maximize production and control competitive weeds, pests and diseases. When considering management effects, it is useful to differentiate between beneficial and detrimental organisms. Pollinators or predators are welcomed by farmers, but they are often affected by management that is targeted at pests and weeds. While this is a common problem with most crops, management of legume systems affect diversity in ways that differ from the effects on other crops.

Weed control – management of non-crop flora

In conventional crops, many non-crop flora species are considered to be 'weeds'. However, many of these weeds may not have detrimental effects on the crop and even provide benefits for agrobiodiversity (Albrecht, 2003). Regardless, the increased control of weeds is responsible for significant declines in flowering plant species, including those once common in agricultural habitats and in any intensively managed crop, herbicide use and tillage practices reduce non-crop vegetation biodiversity (Hole *et al.*, 2005; Swanton *et al.*, 2006). Some legume crops, such as lupins, are very susceptible to post-emergence herbicide application, so to avoid this cultural control methods such as harrowing are used on such legume crops (see Chapter 6, this volume).

Several legume crop species are competitive and suppress non-crop vegetation. However, not all legumes (e.g. peas) are sufficiently vigorous to significantly reduce weed abundance via competition when grown as a single crop (Deveikyte *et al.*, 2009). Reduced weed pressure can also be achieved by deliberate choice of site-specific crops, crop mixtures or rotations, for example by alternating perennial and annual crops (Meiss *et al.*, 2010b) or by intercropping legumes with cereals to increase the competitiveness of the crop mixture and to reduce the need for herbicides (Hauggaard-Nielsen *et al.*, 2001; Poggio, 2005). In organic systems

in particular, white clover–ryegrass leys are included in rotations specifically for the purpose of growing highly nutritious feed for animals, increasing soil fertility and for controlling annual weeds (Hole *et al.*, 2005). The length of the perennial ley is also an important factor influencing weed dynamics due to a balance between species competitiveness and the influence of the lack of disturbance in the ley phase: Anderson (2010) suggests 3 years of lucerne is more beneficial than longer or shorter leys. Reduced weed management can even limit weed populations in the longer term: if weeds act as a food source for seed-feeding organisms, the presence of weeds can encourage the activities of these organisms and reduce the weed seed bank (Meiss *et al.*, 2010a). This in turn can create a positive feedback on overall biodiversity, especially if no- or low-till management is implemented with intercrop mixtures. However, the effects of including legume crops in rotations on weeds vary. The diversity and abundance of certain weed species can either increase or decline, depending on system design, management practices and weed species (Murphy *et al.*, 2006; Graziani *et al.*, 2012). Overall, the impacts of weed management in individual legume-supported cropping systems will depend on how the potential vegetation community is affected, and the competitiveness of the legume versus other crop and non-crop plants. Thus, only a well-planned and well-informed legume-supported crop rotation can help to keep competitive weeds below problematic levels and achieve the target of positive effects on biodiversity.

While legume-supported cropping in Europe is predominantly concerned with herbaceous plants, many leguminous tree species are used in agricultural systems elsewhere. For example, in tropical areas with particularly nutrient-poor soils and where predominantly low-input subsistence farming is practised (Graham and Vance, 2003), material pruned from leguminous trees and hedgerows can be incorporated into the soil, resulting in yield increases of maize (Egbe *et al.*, 1998). Some leguminous tree species such as acacias have additional allelopathic properties leading to enhanced suppression of weed germination from the soil seed bank (El-Khawas and Shehata, 2005). Such use of leguminous tree species for short rotation forestry might also fit in some European systems and could be beneficial for biodiversity via diversified landscapes.

Pest control – management of crop-associated fauna

Legume traits such as high plant N, flowering and extra-floral nectaries make legumes a potential food source not only for pollinators but also for other herbivores which can potentially become pests. In addition, they provide habitat and food sources for potential pest control agents, including predatory and parasitoid insects (Géneau *et al.*, 2012). The diversity of fauna, both beneficial (pollinators and natural enemies) and detrimental (pests) in legume-supported systems, however, is heavily dependent on the type and frequency of chemical pest control as well as crop and rotation management.

Organic systems, which lack pesticides and mineral fertilizers and have different crop rotations compared with conventional ones, are often associated with increased diversity and abundance of fauna. This may be attributed to the

presence of legumes (e.g. Power and Stout, 2011). However, although many studies have demonstrated increased fauna associated with organic practices, it is difficult to determine which component of organic farming is responsible (Gabriel *et al.*, 2013). As well as legume-supported cropping, other organic and integrated management options include: (i) modifications of planting time, tilling regime and fertilizer application in relation to the pests' life cycle; (ii) intercropping to divert pests or attract natural enemies; (iii) using trap crops, natural plant products or biopesticides alone or in combination with synthetic pesticides; or (iv) the deployment of resistant varieties and other measures (Sharma *et al.*, 2005). Thus it is not simple to disentangle the effects of legume cropping from the effects of other practices in organic systems.

Other legume-supported management practices which influence crop fauna include intercropping with legumes, adding them to field margins or including them in rotations. Such practices can provide more diverse resources and habitats for a range of faunal species over both spatial (within fields, across the landscape) and temporal (over a longer period of time) scales. This can reduce pest and disease pressure due to physical barriers and larger spatio-temporal distances between host plants. Such practices can also increase structural complexity of vegetation, providing additional habitats for invertebrate species. Thus cover crops, undersowing, intercropping, legume-based field margins and mulches can increase beneficial invertebrate biodiversity (Curry, 1986; Osler *et al.*, 2000) and the ecosystem services, such as increased biocontrol, provided by it (Hooks and Johnson, 2001; Midega *et al.*, 2009).

Management of fungal disease

Fungicides used to control diseases may have negative effects on symbiotic and neutral fungal organisms and higher trophic levels. Legumes can disrupt host availability for the pathogens, but host plant resistance is the best means of disease control (Stoddard *et al.*, 2010). Furthermore, the risk of fungal infestation of the crop can be reduced (in both legume-supported and conventional cropping systems) by adjusting seed density, water and nitrogen management. Additionally, maintaining sufficient intervals between potential host plants reduce the risk of fungal diseases.

Soil management

In legume-supported cropping systems, tillage and crop rotation are often closely linked. This is because the root morphology of many legumes allows no-till farming practices on the following crop, which leaves the soil structure intact and crop residue on the field surface. This reduces soil disturbance and promotes beneficial insects and earthworms, as well as increasing microbial activity, and helps with preservation of soil organic matter. No-till management further increases the amount and variety of other wildlife due to improved cover, reduced soil compaction and the reduced chance of destroying ground-nesting birds and mammals.

Legume-supported crop rotations, such as those incorporating red clover and soybean, benefit some groups of soil fauna, including earthworms (Jordan *et al.*, 2004). Earthworm populations increase soil aggregate stability and the storage of C and N in a soybean cropping system (Ketterings *et al.*, 1997), but earthworms are affected by soil disturbance (Curry *et al.*, 2002). Impacts of legume cropping on earthworms are therefore moderated by soil management practices. For example, Schmidt *et al.* (2003) assessed the effects of the absence of tillage and the presence of a permanent white clover understorey on earthworm populations in winter wheat cropping systems. They found only a modest effect of the absence of ploughing alone, but the combination of absence of ploughing and presence of a clover understorey greatly increased earthworm populations. This suggests that large earthworm populations in legume-supported cereal cropping systems are primarily supported through the organic matter input from such systems sustaining a food supply throughout the year (Schmidt *et al.*, 2003). The abundance of earthworms is further influenced by the rate at which earthworm populations can recover after disturbance by reproduction and colonization from neighbouring undisturbed soil. For example, at least 2 years of permanent grass/clover cover are required for the full development of earthworm populations, even in highly favourable temperate soils (Schmidt and Curry, 2001). Earthworm populations in crop rotations are therefore likely to fluctuate depending on crop type and management, order of rotation and duration of non-tilled recovery periods. The potential benefit of legumes for earthworms would have to be weighed against potential negative impacts of soil disturbance through tillage.

Small-seeded, dormant and rapidly germinating ruderal plant species are able to take advantage of newly tilled soil. Legume-supported systems incorporating no-till or reduced tillage may see a reduction in the abundance of ruderal non-crop species. Additionally, legume cropping systems, with improved soil quality, may promote seed-feeding soil organisms, as well as higher microbial activity, resulting in faster rates of seed decay. This can reduce seed longevity and create 'weed-suppressive' soil conditions (Meiss *et al.*, 2010a).

Harvesting

The effect of crop residues on subsequent crops depends on the efficiency of harvesting methods and recombination of material into the soil. Increases in N-rich organic matter in soils following some legume crops may promote non-crop vegetation biodiversity. Organic matter of some legumes, such as lucerne, may suppress other plants with allelopathic compounds remaining in the soil after harvesting the crops. To protect ground-breeding birds, small mammals and amphibians while maintaining a habitat and food source for pollinators in forage legumes, it is considered best to harvest lucerne at least 8 cm above the soil surface and not more often than three times per year. This maintains a high regrowth capacity for the plants, optimal quality and profitable regrowth. Leaving strips of the forage legume near field boundaries or within the field in an alternating manner with every harvest provides additional positive effects for biodiversity. These strips could also provide habitat and flowers for pollinators, even if most of the field is cut three times a year (DAFA, 2012).

Legume-supported Cropping Affects Biodiversity at Site and Landscape Scale

Increasing the diversity of crops creates a greater range of habitats and a more heterogeneous landscape, which can increase niche and thus species diversity (Kleijn and Verbeek, 2000; Tschardt et al., 2005). Therefore, adding legumes to the cropping system in regions dominated by cereals (Altieri, 1999) leads to greater spatial and temporal habitat diversity. With a more complex landscape (e.g. with more boundaries between habitat types), biodiversity (including habitat diversity, as well as the abundance and richness of pest and beneficial arthropods) may be enhanced (Duelli, 1997). When legumes are added to crop margins or as cover crops, food resources are provided for beneficial organisms, especially in comparison to where margins or fields are left bare and resources are scarce.

To sustain a diverse community of pollinators in landscapes otherwise dominated by grass and cereals, it is crucial that nectar- and pollen-providing legumes and other plants, including crops, flower (Woodcock et al., 2014) and that pollinators and higher trophic guilds are not affected by non-selective systemic insecticides (Goulson et al., 2015). Furthermore, although they provide a substantial resource for pollinators, legume crops, like most mass-flowering crops, flower for only a short time. Perennial legumes, such as lucerne, have longer flowering periods, so they provide a food source for a wider range of pollinators, especially when other mass-flowering crops such as rapeseed have stopped flowering (Knight et al., 2009; Stanley et al., 2013).

Pollinator responses to legumes in field margins and to different crops depend on the surrounding landscape context and crop management regimes (Knight et al., 2009; Stanley et al., 2013). Different crops or wild flowers attract different pollinators (Rollin et al., 2013; Garratt et al., 2014; Grass et al., 2016), and so planting field-margin floral resources has a bigger effect in arable crops than in forages and in simple rather than complex landscape contexts (Scheper et al., 2013). A landscape with a wider range of crop and non-crop flowers can support a greater diversity of pollinators. As such, legumes can contribute to the landscape-wide diversity in floral resources to support pollinators.

Such changes at the landscape scale have the greatest impact on larger and more mobile organisms such as farmland birds, bats, vertebrates and flying insects through provision of increased foraging and nesting habitats, and range of food, prey or other resources (Wilson et al., 1997; Wolff et al., 2001; Santangeli and Dolman, 2011; Andersson et al., 2013). For example, lucerne crops are significant habitats for other taxa such as grasshoppers (Bretagnolle et al., 2011) and small mammals (common vole and mouse species) that overwinter and reproduce there (Inchausti et al., 2009), and are a main prey for top predators, such as raptors (e.g. Montagu's harrier, *Circus pygargus*; Salamolard et al., 2000). The abundance of these prey species drives the population dynamics of their predators at the landscape scale. An increase in the area of lucerne benefits skylarks (*Alauda arvensis*) (Kragten et al., 2008), ortolan bunting (*Emberiza hortulana*) (Morelli, 2012) or the little bustard (*Tetrax tetrax*) (Bretagnolle et al., 2011), which are birds of high conservation value.

Conclusions

Legume-supported cropping can have significant impacts on biodiversity in agroecosystems, both above and below ground, locally, on individual farms, and at the landscape scale. The relationships between legume crops and non-crop flora and fauna are highly complex, and there is no single overriding positive or negative effect on biodiversity in general.

Overall, increasing the use of legumes will generally improve biodiversity in European agricultural landscapes. Nevertheless, it is important to consider the many factors impacting negatively on biodiversity, such as rotational problems and crop protection measures. Furthermore, alternative implementation measures need to be taken into account to achieve the expectations. It is clear, however, that a more in-depth approach to comparing the biodiversity of legume-supported and conventional cropping over regional and global scales is required before biodiversity costs and benefits can be accurately quantified.

References

- Albrecht, H. (2003) Suitability of arable weeds as indicator organisms to evaluate species conservation effects of management in agricultural ecosystems. *Agriculture, Ecosystems & Environment* 98(1), 201–211.
- Altieri, M.A. (1999) The ecological role of biodiversity in agroecosystems. *Agriculture Ecosystems & Environment* 74(1–3), 19–31.
- Altieri, M.A. and Rogé, P. (2010) The ecological role and enhancement of biodiversity in agriculture. In: Lockie, S. and Carpenter, D. (eds) *Agriculture, Biodiversity and Markets*. Earthscan, London, pp. 15–32.
- Anderson, R.L. (2010) A rotation design to reduce weed density in organic farming. *Renewable Agriculture and Food Systems* 25(03), 189–195.
- Andersson, G.K., Birkhofer, K., Rundlöf, M. and Smith, H.G. (2013) Landscape heterogeneity and farming practice alter the species composition and taxonomic breadth of pollinator communities. *Basic and Applied Ecology* 14(7), 540–546.
- Bilalis, D., Papastylianou, P., Konstantas, A., Patsiali, S., Karkanis, A. and Efthimiadou, A. (2010) Weed-suppressive effects of maize–legume intercropping in organic farming. *International Journal of Pest Management* 56(2), 173–181.
- Blanchart, E., Villenave, C., Viallatoux, A., Barthes, B., Girardin, C., Azontonde, A. and Feller, C. (2006) Long-term effect of a legume cover crop (*Mucuna pruriens* var. *utilis*) on the communities of soil macrofauna and nematofauna, under maize cultivation, in southern Benin. *European Journal of Soil Biology* 42, S136–S144.
- Bommarco, R., Lundin, O., Smith, H.G. and Rundlöf, M. (2012) Drastic historic shifts in bumblebee community composition in Sweden. *Proceedings of the Royal Society B: Biological Sciences* 279(1727), 309–315.
- Bretagnolle, V., Villers, A., Denonfoux, L., Cornulier, T., Inchausti, P. and Badenhausser, I. (2011) Rapid recovery of a depleted population of little bustards *Tetrax tetrax* following provision of alfalfa through an agri-environment scheme. *Ibis* 153(1), 4–13.
- Brookes, B., Small, E., Lefkovitch, L.P., Damman, H. and Fairey, D.T. (1994) Attractiveness of alfalfa (*Medicago sativa* L) to wild pollinators in relation to wildflowers. *Canadian Journal of Plant Science* 74(4), 779–783.

- Carbonero, C.H., Mueller-Harvey, I., Brown, T.A. and Smith, L. (2011) Sainfoin (*Onobrychis viciifolia*): a beneficial forage legume. *Plant Genetic Resources – Characterization and Utilization* 9(1), 70–85.
- Carvell, C., Meek, W.R., Pywell, R.F., Goulson, D. and Nowakowski, M. (2007) Comparing the efficacy of agri-environment schemes to enhance bumble bee abundance and diversity on arable field margins. *Journal of Applied Ecology* 44(1), 29–40.
- Curry, J.P. (1986) Aboveground arthropod fauna of four Swedish cropping systems and its role in carbon and nitrogen cycling. *Journal of Applied Ecology* 23(3), 853–870.
- Curry, J.P., Byrne, D. and Schmidt, O. (2002) Intensive cultivation can drastically reduce earthworm populations in arable land. *European Journal of Soil Biology* 38(2), 127–130.
- Deutsche Agrarforschungsallianz (DAFA) (2012) Fachforum Leguminosen. Wissenschaft, Wirtschaft, Gesellschaft – Ökosystemleistungen von Leguminosen wettbewerbsfähig machen. Forschungsstrategie der Deutschen Agrarforschungsallianz. Available at: www.dafa.de/de/startseite/fachforen/leguminosen.html (accessed 10 October 2016).
- Deveikyte, I., Kadziuliene, Z. and Sarunaite, L. (2009) Weed suppression ability of spring cereal crops and peas in pure and mixed stands. *Agronomy Research* 7 (Special Issue 1), 239–244.
- Duelli, P. (1997) Biodiversity evaluation in agricultural landscapes: an approach at two different scales. *Agriculture, Ecosystems & Environment* 62(2), 81–91.
- Egbe, E.A., Ladipo, D.O., Nwoboshi, L.C. and Swift, M.J. (1998) Potentials of *Millettia thonningii* and *Pterocarpus santalinoides* for alley cropping in humid lowlands of West Africa. *Agroforestry Systems* 40(3), 309–321.
- EI-Khawas, S.A. and Shehata, M.M. (2005) The allelopathic potentialities of *Acacia nilotica* and *Eucalyptus rostrata* on monocot (*Zea mays* L.) and dicot (*Phaseolus vulgaris* L.) plants. *Biotechnology* 4(1), 23–34.
- Everwand, G., Rösch, V., Tschardtke, T. and Scherber, C. (2014) Disentangling direct and indirect effects of experimental grassland management and plant functional-group manipulation on plant and leafhopper diversity. *BMC Ecology* 14(1), 1.
- Frankow-Lindberg, B.E., Brophy, C., Collins, R.P. and Connolly, J. (2009) Biodiversity effects on yield and unsown species invasion in a temperate forage ecosystem. *Annals of Botany* 103(6), 913–921.
- Gabriel, D., Sait, S.M., Kunin, W.E. and Benton, T.G. (2013) Food production vs. biodiversity: comparing organic and conventional agriculture. *Journal of Applied Ecology* 50(2), 355–364.
- Garratt, M.P., Coston, D.J., Truslove, C., Lappage, M., Polce, C., Dean, R., Biesmeijer, J. and Potts, S.G. (2014) The identity of crop pollinators helps target conservation for improved ecosystem services. *Biological Conservation* 169, 128–135.
- Géneau, C.E., Wäckers, F.L., Luka, H., Daniel, C. and Balmer, O. (2012) Selective flowers to enhance biological control of cabbage pests by parasitoids. *Basic and Applied Ecology* 13(1), 85–93.
- Ghazoul, J. (2006) Floral diversity and the facilitation of pollination. *Journal of Ecology* 94(2), 295–304.
- Goulson, D., Nicholls, E., Botías, C. and Rotheray, E.L. (2015) Bee declines driven by combined stress from parasites, pesticides, and lack of flowers. *Science* 347(6229), 1255957.
- Graham, P.H. and Vance, C.P. (2003) Legumes: importance and constraints to greater use. *Plant Physiology* 131(3), 872–877.
- Grass, I., Albrecht, J., Jauker, F., Diekötter, T., Warzecha, D., Wolters, V. and Farwig, N. (2016) Much more than bees – wildflower plantings support highly diverse flower-visitor communities from complex to structurally simple agricultural landscapes. *Agriculture, Ecosystems & Environment* 225, 45–53.
- Graziani, F., Onofri, A., Pannacci, E., Tei, F. and Guiducci, M. (2012) Size and composition of weed seedbank in long-term organic and conventional low-input cropping systems. *European Journal of Agronomy* 39, 52–61.

- Hauggaard-Nielsen, H., Ambus, P. and Jensen, E.S. (2001) Interspecific competition, N use and interference with weeds in pea–barley intercropping. *Field Crops Research* 70(2), 101–109.
- Hole, D.G., Perkins, A.J., Wilson, J.D., Alexander, I.H., Grice, P.V. and Evans, A.D. (2005) Does organic farming benefit biodiversity? *Biological Conservation* 122(1), 113–130.
- Hooks, C.R.R. and Johnson, M.W. (2001) Broccoli growth parameters and level of head infestations in simple and mixed plantings: impact of increased flora diversification. *Annals of Applied Biology* 138(3), 269–280.
- Inchausti, P., Carslake, D., Attié, C. and Bretagnolle, V. (2009) Is there direct and delayed density dependent variation in population structure in a temperate European cyclic vole population? *Oikos* 118(8), 1201–1211.
- Jordan, D., Miles, R.J., Hubbard, V.C. and Lorenz, T. (2004) Effect of management practices and cropping systems on earthworm abundance and microbial activity in Sanborn Field: a 115-year-old agricultural field. *Pedobiologia* 48(2), 99–110.
- Ketterings, Q.M., Blair, J.M. and Marinissen, J.C.Y. (1997) Effects of earthworms on soil aggregate stability and carbon and nitrogen storage in a legume cover crop agroecosystem. *Soil Biology and Biochemistry* 29(3–4), 401–408.
- Kleijn, D. and Verbeek, M. (2000) Factors affecting the species composition of arable field boundary vegetation. *Journal of Applied Ecology* 37(2), 256–266.
- Knight, M.E., Osborne, J.L., Sanderson, R.A., Hale, R.J., Martin, A.P. and Goulson, D. (2009) Bumblebee nest density and the scale of available forage in arable landscapes. *Insect Conservation and Diversity* 2(2), 116–124.
- Kragten, S., Trimbos, K.B. and de Snoo, G.R. (2008) Breeding skylarks (*Alauda arvensis*) on organic and conventional arable farms in the Netherlands. *Agriculture, Ecosystems & Environment* 126(3), 163–167.
- Kumar, K., Goh, K.M. and Donald, L.S. (1999) Crop residues and management practices: effects on soil quality, soil nitrogen dynamics, crop yield, and nitrogen recovery. *Advances in Agronomy* 68, 197–319.
- Lagerlof, J., Andren, O. and Paustian, K. (1989) Dynamics and contribution to carbon flows of Enchytraeidae (Oligochaeta) under four cropping systems. *Journal of Applied Ecology* 26(1), 183–199.
- Leppik, E.E. (1966) Floral evolution and pollination in the Leguminosae. *Annales Botanici Fennici* 3(3), 299–308.
- Lupwayi, N.Z. and Kennedy, A.C. (2007) Grain legumes in northern great plains. *Agronomy Journal* 99(6), 1700–1709.
- Mader, E. and Hopwood, J. (2013) *Pollinator Management for Organic Seed Producers*. The Xerxes Society, Portland, Oregon.
- Meiss, H., Le Lagadec, L., Munier-Jolain, N., Waldhardt, R. and Petit, S. (2010a) Weed seed predation increases with vegetation cover in perennial forage crops. *Agriculture, Ecosystems & Environment* 138(1–2), 10–16.
- Meiss, H., Médiène, S., Waldhardt, R., Caneill, J., Bretagnolle, V., Reboud, X. and Munier-Jolain, N. (2010b) Perennial lucerne affects weed community trajectories in grain crop rotations. *Weed Research* 50(4), 331–340.
- Meiss, H., Médiène, S., Waldhardt, R., Caneill, J. and Munier-Jolain, N. (2010c) Contrasting weed species composition in perennial alfalfas and six annual crops: implications for integrated weed management. *Agronomy for Sustainable Development* 30(3), 657–666.
- Midega, C.A.O., Khan, Z.R., Van den Berg, J., Ogol, C.K.P.O., Bruce, T.J. and Pickett, J.A. (2009) Non-target effects of the ‘push-pull’ habitat management strategy: parasitoid activity and soil fauna abundance. *Crop Protection* 28(12), 1045–1051.
- Moorcroft, D., Whittingham, M., Bradbury, R. and Wilson, J. (2002) The selection of stubble fields by wintering granivorous birds reflects vegetation cover and food abundance. *Journal of Applied Ecology* 39(3), 535–547.

- Morelli, F. (2012) Correlations between landscape features and crop type and the occurrence of the ortolan bunting *Emberiza hortulana* in farmlands of Central Italy. *Ornis Fennica* 89(4), 264.
- Murphy, S.D., Clements, D.R., Belaoussoff, S., Kevan, P.G. and Swanton, C.J. (2006) Promotion of weed species diversity and reduction of weed seedbanks with conservation tillage and crop rotation. *Weed Science* 54(1), 69–77.
- Mytton, L.R., Cresswell, A. and Colbourn, P. (1993) Improvement in soil structure associated with white clover. *Grass and Forage Science* 48(1), 84–90.
- Osler, G.H.R., van Vliet, P.C.J., Gauci, C.S. and Abbott, L.K. (2000) Changes in free living soil nematode and microarthropod communities under a canola–wheat–lupin rotation in Western Australia. *Australian Journal of Soil Research* 38(1), 47–59.
- Palmer, R.G., Perez, P.T., Ortiz-Perez, E., Maalouf, F. and Suso, M.J. (2009) The role of crop–pollinator relationships in breeding for pollinator-friendly legumes: from a breeding perspective. *Euphytica* 170(1/2), 35.
- Poggio, S.L. (2005) Structure of weed communities occurring in monoculture and intercropping of field pea and barley. *Agriculture, Ecosystems and Environment* 109(1–2), 48–58.
- Potts, S.G., Woodcock, B.A., Roberts, S.P.M., Tscheulin, T., Pilgrim, E.S., Brown, V.K. and Tallowin, J.R. (2009) Enhancing pollinator biodiversity in intensive grasslands. *Journal of Applied Ecology* 46(2), 369–379.
- Power, E.F. and Stout, J.C. (2011) Organic dairy farming: impacts on insect–flower interaction networks and pollination. *Journal of Applied Ecology* 48(3), 561–569.
- Price, P.W., Bouton, C.E., Gross, P., McPherson, B.A., Thompson, J.N. and Weis, A.E. (1980) Interactions among three trophic levels: influence of plants on interactions between insect herbivores and natural enemies. *Annual Review of Ecology and Systematics* 11, 41–65.
- Rollin, O., Bretagnolle, V., Decourtye, A., Aptel, J., Michel, N., Vaissière, B.E. and Henry, M. (2013) Differences of floral resource use between honey bees and wild bees in an intensive farming system. *Agriculture, Ecosystems and Environment* 179, 78–86.
- Salamolard, M., Butet, A., Leroux, A. and Bretagnolle, V. (2000) Responses of an avian predator to variations in prey density at a temperate latitude. *Ecology* 81(9), 2428–2441.
- Santangeli, A. and Dolman, P.M. (2011) Density and habitat preferences of male little bustard across contrasting agro-pastoral landscapes in Sardinia (Italy). *European Journal of Wildlife Research* 57(4), 805–815.
- Scheper, J., Holzschuh, A., Kuussaari, M., Potts, S.G., Rundlof, M., Smith, H.G. and Kleijn, D. (2013) Environmental factors driving the effectiveness of European agri-environmental measures in mitigating pollinator loss – a meta-analysis. *Ecology Letters* 16(7), 912–920.
- Schmidt, O. and Curry, J.P. (1999) Effects of earthworms on biomass production, nitrogen allocation and nitrogen transfer in wheat–clover intercropping model systems. *Plant and Soil* 214(1–2), 187–198.
- Schmidt, O. and Curry, J.P. (2001) Population dynamics of earthworms (Lumbricidae) and their role in nitrogen turnover in wheat and wheatclover cropping systems. *Pedobiologia* 45(2), 174–187.
- Schmidt, O., Clements, R. and Donaldson, G. (2003) Why do cereal–legume intercrops support large earthworm populations? *Applied Soil Ecology* 22(2), 181–190.
- Sharma, H.C., Clement, S.L., Ridsdill-Smith, T.J., Ranga Rao, G.V., El Bouhssini, M., Ujagir, R., Srivastava, C.P. and Miles, M. (2005) Insect pest management in food legumes: the future strategies. In: *Proceedings of the Fourth International Food Legumes Research Conference*, New Delhi, India, 18–22 October 2005. Indian Society of Genetics and Plant Breeding, New Delhi, pp. 522–544.
- Sileshi, G. and Mafongoya, P.L. (2007) Quantity and quality of organic inputs from coppicing leguminous trees influence abundance of soil macrofauna in maize crops in eastern Zambia. *Biology and Fertility of Soils* 43(3), 333–340.

- Sileshi, G., Mafongoya, P.L., Chintu, R. and Akinnifesi, F.K. (2008) Mixed-species legume fallows affect faunal abundance and richness and N cycling compared to single species in maize–fallow rotations. *Soil Biology and Biochemistry* 40(12), 3065–3075.
- Stanley, D.A., Knight, M.E. and Stout, J.C. (2013) Ecological variation in response to mass-flowering oilseed rape and surrounding landscape composition by members of a cryptic bumblebee complex. *PLoS ONE* 8(6), e65516.
- Stoddard, F., Nicholas, A., Rubiales, D., Thomas, J. and Villegas-Fernández, A. (2010) Integrated pest management in faba bean. *Field Crops Research* 115(3), 308–318.
- Sugiyama, A. and Yazaki, K. (2012) Root exudates of legume plants and their involvement in interactions with soil microbes. In: Vivanco, J.M. and Baluska, F. (eds) *Secretions and Exudates in Biological Systems*. Springer, Heidelberg, Germany, pp. 27–48.
- Swanton, C.J., Booth, B.D., Chandler, K., Clements, D.R. and Shrestha, A. (2006) Management in a modified no-tillage corn–soybean–wheat rotation influences weed population and community dynamics. *Weed Science* 54(1), 47–58.
- Tilman, D., Knops, J., Wedin, D., Reich, P., Ritchie, M. and Siemann, E. (1997) The influence of functional diversity and composition on ecosystem processes. *Science* 277(5330), 1300–1302.
- Tilman, D., Cassman, K.G., Matson, P.A., Naylor, R. and Polasky, S. (2002) Agricultural sustainability and intensive production practices. *Nature* 418(6898), 671–677.
- Tscharntke, T., Klein, A.M., Kruess, A., Steffan-Dewenter, I. and Thies, C. (2005) Landscape perspectives on agricultural intensification and biodiversity–ecosystem service management. *Ecology Letters* 8(8), 857–874.
- van Eekeren, N., van Liere, D., de Vries, F., Rutgers, M., de Goede, R. and Brussaard, L. (2009) A mixture of grass and clover combines the positive effects of both plant species on selected soil biota. *Applied Soil Ecology* 42(3), 254–263.
- Wilson, J.D., Evans, J., Browne, S.J. and King, J.R. (1997) Territory distribution and breeding success of skylarks *Alauda arvensis* on organic and intensive farmland in southern England. *Journal of Applied Ecology* 34(6), 1462–1478.
- Wolff, A., Paul, J.P., Martin, J.L. and Bretagnolle, V. (2001) The benefits of extensive agriculture to birds: the case of the little bustard. *Journal of Applied Ecology* 38(5), 963–975.
- Woodcock, B.A., Savage, J., Bullock, J.M., Nowakowski, M., Orr, R., Tallwin, J.R.B. and Pywell, R.F. (2014) Enhancing floral resources for pollinators in productive agricultural grasslands. *Biological Conservation* 171, 44–51.
- Xuan, T.D. and Tsuzuki, E. (2002) Varietal differences in allelopathic potential of alfalfa. *Journal of Agronomy and Crop Science* 188(1), 2–7.

5

Grain Legumes: an Overview

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Abstract

The grain legumes are important sources of protein in animal and human diets. This chapter provides an overview of some basic aspects of their biology and production in Europe. All early agricultural societies apparently domesticated a grain legume at much the same time as a cereal, perhaps indicating that their nutritional value was noticed. The cool-season grain legumes came to Europe from the Middle East with arable agriculture, followed in historical times by common bean from the Americas and soybean from China. The basic growth habit is indeterminate, with simultaneous flowering and pod filling. Most species are self-pollinating but produce more flowers than can mature as pods. The cool-season starchy species (pea, faba bean, lentil and chickpea) have many attributes in common, including parallel diseases. The lupins (white, narrow-leafed and yellow) form a closer cluster, and have an unusual seed composition where the main energy store for germination is cell wall material. The number of warm-season legume species is large, but only two, common bean and soybean, are important in Europe. Seed size is highly variable in the cool-season species and common bean, and seed colour in all species. Many cultures prefer specific sizes and colours for food use. A wide range of antinutritional substances has evolved to protect legume seeds from predators, and humans have developed methods to remove or denature them, or reduce them through breeding, in order to improve quality for food and feed.

Introduction

The legume family (*Fabaceae*) is one of the largest families of flowering plants. The unifying feature of the family is the characteristic legume pod with a double row of ovules. The family is also characterized by flowers with five fused sepals and five petals. The wide diversity of about 20,000 species comes from adaptability, particularly to nutritionally poor environments, helped by the ability of most

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species to biologically fix nitrogen in symbiosis with bacteria of the *Rhizobiaceae*. According to the current model, early in the evolution of the legumes, a copy of the basic plant–mycorrhizal fungus recognition system was harnessed (neofunctionalized, in evolutionary jargon) to recognize nitrogen-fixing bacteria. Another co-evolutionary process occurred above ground, as the flowers and bees became adapted to each other for pollination.

In agriculture, the legume family is second in importance only to the cereals (*Poaceae*), based on area harvested and total world production, with more than 650 million t of grain legumes produced on 240 million ha in 2011 (FAOSTAT, 2016). Several roles attributed to the legumes are often overlooked. Grain legumes provide one-third of the plant protein and a similar proportion of the vegetable oil used for human consumption (Graham and Vance, 2003). The amino acid composition of legumes complements that of cereals and root crops (Wang *et al.*, 2003), perhaps explaining why the two groups were domesticated together (Gepts, 2004). Legumes are also important forage crops in temperate and tropical regions.

Legumes provide essential minerals for the consumer (Grusak, 2002). In addition, the secondary metabolites that protect the plant against pathogens and pests (e.g. see Ndakidemi and Dakora, 2003) may also protect the human consumer against certain cancers (Madar and Stark, 2002) and have some benefit in the treatment of diabetes (Jenkins *et al.*, 2003). The consumption of grain legumes can reduce cholesterol in blood, and shows a hypoglycaemic effect. Other secondary compounds include antinutritional factors, such as trypsin inhibitors (Gupta, 1987) and allergens (Spergel and Fiedler, 2001).

The family has been traditionally divided into three subfamilies: *Caesalpinioideae*, *Mimosoideae* and *Papilionoideae*, the latter comprising 28 tribes and including the grain legumes along with the important forage legumes (Fig. 5.1). The cool-season legumes (tribes *Fabeae*, *Cicereae* and *Trifolieae*) are closely related and highly similar at the genome level, and slightly removed from the *Genisteae* (Wojciechowski *et al.*, 2004), and the warm-season legumes (tribe *Phaseoleae*) are similarly closely related (Lee *et al.*, 2001) (Fig. 5.1).

The *Fabaceae*, together with a range of less important plants, play a vital role in biological nitrogen fixation (BNF), which is tens of times more effective taking place in symbiosis than in free-living bacteria. It was only in the final quarter of the 20th century that more nitrogen was fixed in the manufacture of synthetic fertilizer than by BNF. Although ancient farmers would not have known how the legumes worked, they certainly noticed the effect of the legume on the following crop, as was made clear by Columella in ancient Rome (Evans, 1998).

Since legume crops can fix their own nitrogen, the question of ‘starter nitrogen’ is often raised: should the farmer apply some N fertilizer to assist with crop establishment until symbiotic nitrogen fixation is active, and if so, how much? Hence, agronomists in many countries recommend the application of 20–40 kg/ha of N fertilizer at sowing time.

Origin and Spread in Europe

The movement of early Neolithic agriculture into south-west Asia and then the Mediterranean Basin is fairly well documented from the archaeological record.

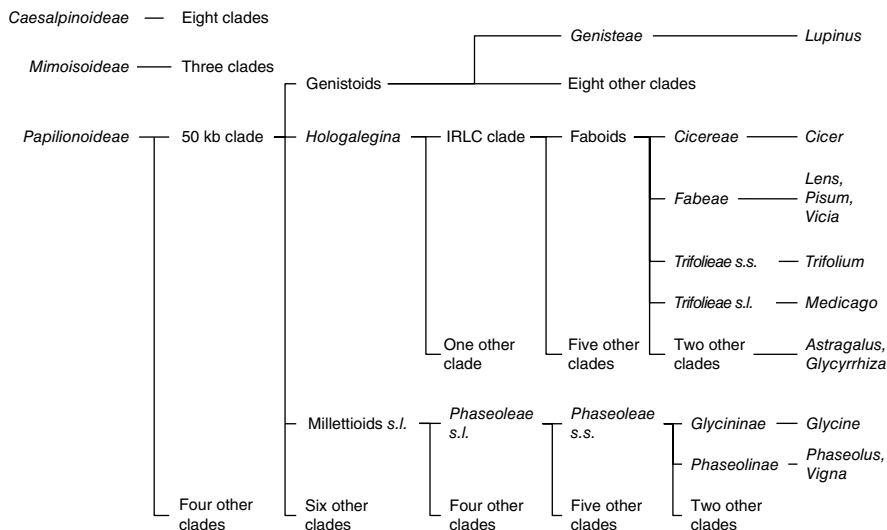


Fig. 5.1. Phylogeny of the legumes, arranged to highlight the genera that include important crops in Europe. IRLC, Invert repeat lacking clade; s.s., *sensu stricto*; s.l., *sensu lato*. (Adapted from LOWO, 2013.)

The most numerous grain remains found in early farming villages come from three cereals: (i) emmer wheat (*Triticum turgidum* subsp. *dicoccum* Schrank ex Schulber); (ii) einkorn wheat (*Triticum monococcum* subsp. *monococcum* L.); and (iii) barley (*Hordeum vulgare* L.). Several grain legumes appear as companions of the cereals, as far back as 10,000 BC, and the most frequent of these in the Fertile Crescent are lentil (*Lens culinaris* Medik.), common pea (*Pisum sativum* L.) and bitter vetch (*Vicia ervilia* (L.) Willd.) (Zohary and Hopf, 2000), the latter now hardly cultivated. Faba bean (*Vicia faba* L.) and chickpea (*Cicer arretinum* L.) are now understood to be part of that initial round of domestication, and their apparent rarity is attributed to the fragility of the carbonized seeds (Tanno and Willcox, 2006). As agriculture started in other parts of the world, a grain legume was always among the early domesticates, with common bean (*Phaseolus vulgaris* L.) having been brought into cultivation in Central and South America, and soybean (*Glycine max* L.) in China. Lupins, with their adaptation to acid, sandy soils, were brought into cultivation much later, in the first millennium BC. Lucerne (alfalfa) (*Medicago sativa* L.) was taken into use for horse feed in Bronze Age Anatolia. The records of the exploitation of clovers and other forage legumes, in contrast, began in Spain around AD 1000 and spread beyond the Pyrenees after about AD 1500 (Kjaergaard, 2003). Vetches (*Vicia* spp. other than faba bean) sit on the boundary between forages and grain legumes, being primarily grown for forage purposes but having sufficiently large seeds to be developed for grain use, if certain antinutritional factors can be overcome.

Grain legumes have been used for food for thousands of years and their history is tightly linked with the evolution of human civilization. They remain vital in the nutrition of many societies, although they have been replaced as protein sources by meat, sometimes excessively in many other countries where they

retain importance as animal feed. Furthermore, most are also consumed as green vegetables when the seeds and/or pods are immature.

The Cool-season Starchy Legumes

The grain legumes in the *Faboid* clade have many characteristics in common. Germination is hypogeal, meaning that the cotyledons and cotyledonary buds remain under the soil surface, and if the emergent shoot is damaged, it can be replaced by new shoots from the axils of the cotyledons. The seedlings are generally tolerant of mild frosts, from -4°C in lentil to -10°C in some spring-sown cultivars of faba bean and pea. The leaves are pinnately compound, with oval leaflets generally ending in tendrils (reduced to a point in faba bean). A pair of stipules clasps the stem at the node. After a certain number of nodes of vegetative growth, racemes of flowers are produced in the leaf axils (Fig. 5.2). The induction of flowering is either day-neutral (not affected by day length) or long-day (promoted by increasing day length above a certain minimum value). Flowers and developing seeds are



Fig. 5.2. (A) Faba bean at flowering stage, showing axillary racemes of four to six flowers, and the stipules clasping the stem at the node. (B) White lupin at flowering stage, showing palmately compound leaves and long, terminal inflorescence.

not tolerant of frost. The basic growth habit is indeterminate, with flowering and podding continuing as long as conditions allow. Heat and water deficit are the stresses most likely to halt growth, and moderate stress late in the growing season is often desirable in order to bring the crop to a harvestable state. The number of flowers per raceme is generally determined by genotype, and the number of seeds per pod (on which pod length depends) is strongly determined in that way, while the number of flowering nodes is substantially affected by environment. Sowing is usually in the spring in continental, oceanic and boreal climates, and in the autumn in Mediterranean climates. Autumn-sown faba bean and pea have been developed in oceanic climates and efforts continue to increase their frost tolerance so they can be grown in some continental climates.

Seed size is determined by the size of the pod (Patrick and Stoddard, 2010), which is maternal tissue and determined primarily by the genotype of the mother plant. Severely restricting growing conditions late in the grain-filling period may reduce seed size, but most legumes in such conditions abort pods as a first measure to reduce sink strength, thereby preserving seed size and hence seedling vigour in the next generation. Within a pod, individual ovules may not get fertilized, or individual developing seeds may abort due to some nutritional or mutational cause, but these losses are minor.

None of these species is considered particularly tolerant of drought, flooding, heat or salinity, although there are marginal differences between them, and considerable genetic variation within each one that can be harnessed through plant breeding (Stoddard *et al.*, 2006). Chickpea is considered the most heat-tolerant, both chickpea and lentil are relatively drought-tolerant, and faba bean is the most tolerant of waterlogging.

Rhizobium leguminosarum is the nitrogen-fixing symbiont for most of these species, with several biovars having been selected for optimum performance on individual hosts. Chickpea requires *Rhizobium ciceri*.

The protein concentration in the seeds is 20–25% (higher in faba bean). Their main energy store is starch, in ovoid granules about 15 μm \times 25 μm , comprising 40–50% of the seed's dry matter. The amylose (long-chain, essentially unbranched molecules) content of the starch is 30–35%, which is higher than in most cereals, contributing to the slow digestibility of legume starch, which is valuable for lowering the glycemic index and maintaining satiety of the consumer (Stoddard, 2004). The oil concentration is low, around 1% of dry matter except for chickpea which is 3–6% oil, and its main fatty acid is linoleic (Lizarazo *et al.*, 2015).

The most important and widespread insect pests are aphids (*Aphis fabae*, the black bean aphid, and *Acyrtosiphon pisum*, the green pea aphid), leaf weevils (*Sitona lineatus* and other species), seed weevils or bruchids (*Bruchus pisorum* on pea, *Bruchus rufimanus* on faba bean and *Bruchus lentis* on lentil), and the pea moth (*Cydia nigricana*). The aphids are important not only because of the direct damage they do but also for their role as virus vectors. The adult leaf weevils reduce the photosynthetic area of young seedlings, and their larvae do worse damage by consuming root nodules. Bruchids are the hardest to control, as the larvae develop within the seed and are protected from contact insecticides.

The main pathogens are sets of closely related fungi (Tivoli *et al.*, 2006). Each has a leaf, pod and stem blight of the genus *Ascochyta*: (i) *Ascochyta fabae*

on faba bean and lentil; (ii) *Ascochyta rabiei* on chickpea; and (iii) *Ascochyta pisi* together with *Mycosphaerella pinodes* and *Phoma medicaginis* var. *pinodella* on pea. These diseases are splash-dispersed and have a low optimum temperature for growth, so are most prevalent on autumn-sown crops in Mediterranean and oceanic climates. The sclerotia of the perfect stage can last up to 3 years in the soil, so a minimum 4-year rotation is recommended. Each has a rust: (i) *Uromyces viciae-fabae* on faba bean and lentil; (ii) *Uromyces pisi* on pea; and (iii) *Uromyces ciceris-arietini* on chickpea. The rusts grow best in warm, relatively humid weather, such as late summer in a continental climate. In other climates, they often arrive so late in the growing season that they help to desiccate the nearly mature crop. Chocolate spot disease, caused by *Botrytis fabae*, is exclusive to and important on faba bean and some vetches, while *Botrytis cinerea*, grey mould, is occasionally found on pea, lentil and chickpea, and is sometimes considered to contribute to chocolate spot disease on faba bean. These fungi can cause catastrophic crop losses when plant surfaces remain wet for a prolonged period and temperatures are close to 20°C, but are seldom problematic in other conditions (Stoddard *et al.*, 2010). *Peronospora viciae* causes downy mildew on pea, faba bean, lentil and some vetches. The literature on its interaction with pea is larger than that on the rest of its hosts combined, suggesting that it is most important on that crop, and it is this author's experience that downy mildew is not detectable on faba bean until the other three diseases are controlled. Because of these diseases, and their ability to survive in the soil, it is widely recommended that grain legumes are used no more often than every fourth year in the cropping sequence.

Aphanomyces euteiches is an oomycete that has become the major limitation to growing pea in many parts of the world, as it causes a root rot disease and persists in the soil for up to 9 years, so rotations have to be at least that long. Lentil is considered generally susceptible, but resistance exists in some accessions of faba bean and vetches (Moussart *et al.*, 2013).

Broomrapes (*Orobanchaceae*) are flowering plants that parasitize the roots of many crops and are particularly limiting in Mediterranean climates. *Orobanche crenata* Forsk. is the most common one attacking pea, faba bean, lentil and vetches, but most germplasm of chickpea is resistant to it (Rubiales *et al.*, 2004).

The cool-season grain legumes are generally seen as poorly competitive with weeds, owing to relatively slow establishment after sowing and, in several species, low levels of crop cover and thus shading of the ground from the small leaflets and tendrils. Unfortunately, few herbicides are suitable for use on legumes, and even fewer are approved for use on legumes in European countries, so weed control remains difficult. The use of anti-weed net on the soil is an option for weed control in high-value food crops.

Except for the largest-seeded cultivars of faba bean, common bean and chickpea, conventional sowing and harvesting machinery can be used for all of the grain legumes. Target crop densities depend on many factors and local agronomists should be consulted, but the following figures (per square metre) can be used as starting points: 20 for winter faba bean, 30–50 for chickpea, 50–70 for spring faba bean, 70–100 for pea and 140–160 for lentil. Sowing depth is usually three to four times the seed diameter.

The species are presented below in order of the quantity harvested in Europe as mapped by Eurostat, comprising the European Union (EU) and all other European countries west of the former Soviet Union. Eurostat data are not available for lentil, chickpea or common bean, so FAOSTAT data are used for these, according to the Eurostat countries.

Pea

Pea is the most widely grown grain legume in Europe and the fourth most grown in the world (FAOSTAT, 2016). According to Eurostat, total European production in 2013 was 1.26 million t, of which 39% was harvested in France (Fig. 5.3). Pea is also one of the most widely grown vegetables, as a mutation in the gene coding for starch-branching enzyme I leads to a reduction in synthesis of the amylopectin fraction of starch that is not compensated by increased amylose synthesis (Bhattacharyya *et al.*, 1990), so sucrose accumulates in the seed, making it pleasant to eat and causing it to wrinkle when it dries. The pea pod can also be eaten fresh, when it lacks the inner layer of parchment. A new type of horticultural pea, currently grown in Spain, is the ‘tear pea’, whose grain is consumed very tender and almost raw, with a size of about 3 mm and a sweet taste. By its sensory qualities it is called ‘vegetable caviar’. Peas grown for dry use as food or feed are generally smooth and round, and dimpled or blocky cultivars are desired for specific food markets.

Seed size varies from 100 mg to 350 mg, but the majority of cultivars have seeds of 200–250 mg. ‘Marrowfat’ cultivars are at the large end of the size

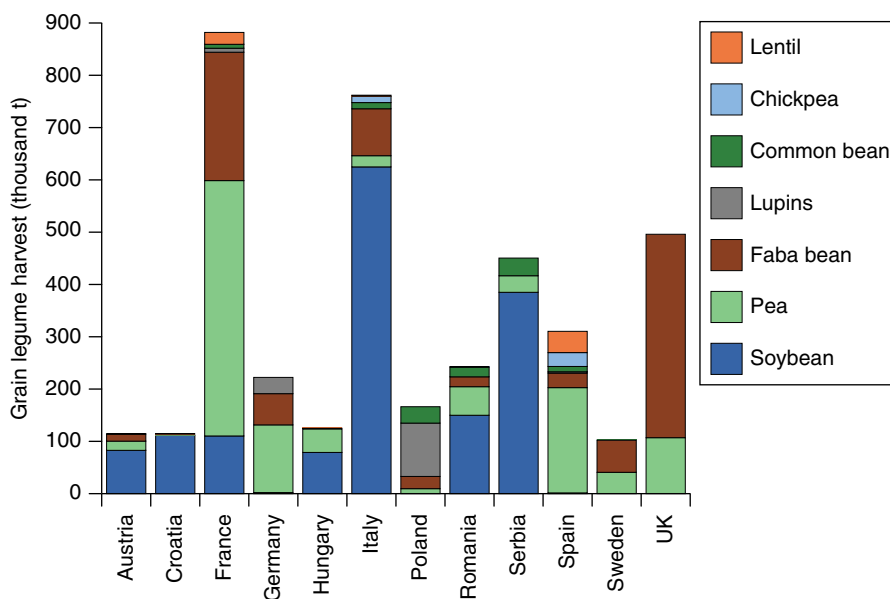


Fig. 5.3. Production of grain legumes in the 12 European countries where the total harvest exceeded 100,000 t in 2013. Data from Eurostat (2016) (faba bean, pea, soybean, lupins) and FAOSTAT (2016) (lentil, chickpea, common bean).

distribution and the seeds are angular rather than round. Cotyledons are either yellow or green, depending on the degradation of chlorophyll during maturation. Most cultivars have white flowers and tannin-free seed coats that are either colourless or pale green, but autumn-sown cultivars and whole-crop forage cultivars have coloured flowers and seed coats. Starting at node 12–16, racemes bearing one to three flowers are borne in the leaf axils. Self-pollination reliably occurs before anthesis and the scentless flowers do not attract pollinating insects. Most cultivars produce between six and ten seeds per pod.

Pea evolved as a tendril-supported climber and its stems are weak. Modern semi-leafless cultivars, where the leaflets are converted to tendrils (gene *af*) and the stipules are greatly enlarged to provide photosynthetic area (gene *St*), support themselves in pure stands by clinging to each other, with greatly reduced lodging in spite of the weakness of the stems. Spring-sown cultivars generally produce one stem and rarely branch, whereas autumn-sown cultivars usually produce three to five stems from the base. Increased basal branching would allow seeding rates to be reduced, but could lead to undesirably later flowering and maturity, unless handled carefully in the breeding programme.

The most important antinutritional factor restricting use in animal feed is trypsin inhibitor (TI). Different TI forms protect the crops from various bruchids so are valuable in crop production, but unless the feed is heat-moisture treated to denature them, they reduce feed conversion efficiency and cause stress to the consuming animal's pancreas. Hence low-TI germplasm has been developed for feed purposes, but it requires better segregation in the crop-handling chain than is currently possible, so it has made little market impact.

Faba bean

Faba bean is a preferred food in West Asia, North Africa and China, while it is more widely popular as a green vegetable and in many countries is used as feed. In spite of its widespread use, the global faba bean area decreased from 5 million ha in 1965 to 2.7 million ha in 2011 (FAOSTAT, 2016). Faba bean production in Europe (Eurostat, 2016) was 1.40 million t in 2013, and the largest producer was the UK producing 0.39 million t (Fig. 5.3). As a result of the strong collaborative research and breeding programmes during the last 40 years, considerable progress has been made in reduction of antinutritional factors, improvement in biotic and abiotic stress resistance, and altered growth habit. Faba bean, among legumes, is a particularly important candidate for increasing BNF in temperate agricultural systems due to its high productivity of dry matter and high proportion of nitrogen derived from the atmosphere (Baddeley *et al.*, 2013). Faba bean is well adapted to heavy clay soils with a pH of 6–8, and its growth suffers when the pH is below 5. Its taproot is larger and more robust than that of the other cool-season legumes.

Seed size is exceptionally variable in this species, leading to a complex nomenclature. Accessions with seeds < 250 mg are placed in var. *paucijuga*, and larger-seeded materials are in var. *faba*, with three subdivisions: (i) *minor* (< 500 mg); (ii) *equina* (500–800 mg); and (iii) *major* (> 800 mg). The *major* types, known

in English as broad beans, can have seeds up to 3 g in size. The distinctions of *minor*, *equina* and *major* are for commercial convenience and have no botanical value, as seed size and other traits are continuously distributed. Small seeds are round, almost as round as peas, and large seeds are flat. Seed protein concentration is higher in faba bean than in the other cool-season starchy legumes, with a world average around 29% and values in favoured situations approaching 35% (Crépon *et al.*, 2010). Many faba bean breeders aim to increase seed protein concentration further.

The first factors limiting use of faba bean are the pyrimidine glycosides, vicine and convicine that comprise about 1% of the dry weight of wild-type seeds (Khamassi *et al.*, 2013). The aglycones, divicine and isouramil are powerful oxidants that cause acute haemolytic anaemia (termed 'favism') in susceptible humans with a deficiency in glucose-6-phosphate dehydrogenase, and also in chickens (Crépon *et al.*, 2010). The *vc*- gene reduces the vicine-convicine content below one-tenth of normal values, to levels that are considered safe, and has been used in the breeding of several French cultivars.

As in pea, autumn-sown cultivars produce many stems but spring-sown ones generally produce only one. Spring cultivars most often produce their first flowers in the axil of the seventh true leaf, but a landrace that flowers at the third true leaf has recently been identified. Autumn-sown cultivars require some vernalization (weeks of chilling at 0–4°C) in order to flower (Link *et al.*, 2010), so the node count is less certain. The number of flowers per raceme is highly variable and can be as high as 15, but is more usually around four to six (Fig. 5.2). Most cultivars produce three to four seeds per pod, and some produce up to ten.

Faba bean, unlike the other cool-season legumes, has a mixed breeding system, with both self- and cross-pollination. Within a mixed population such as a landrace or a composite cultivar, hybrid individuals are generally able to pollinate themselves ('autofertile'), while inbred individuals are reliant on bee activity to bring pollen into contact with the stigma (reviewed by Stoddard and Bond, 1987). The corolla tube is too long for honeybees or short-tongued bumblebees to reach the nectar, but they can gather pollen, while long-tongued bumblebees and other wild bees make use of the nectar as well as the pollen. Depending on the cultivar, its level of inbreeding, its autofertility, and the available population of pollinators, outcrossing rates range from essentially zero to 83%. This feature affects seed multiplication in a breeding programme, as the valuable early-generation seed crop must be isolated from other sources of pollen by distance or in a cage. It also confers a positive environmental impact, as flowering faba bean crops support populations of wild bees. A related aspect of the reproductive biology is the production of excess flowers that serve to attract pollinators, thus providing an evolutionary advantage by sending the pollen further than the seeds can spread. Novices growing faba bean for the first time are often distressed by the loss of flowers, but this is seldom due to lack of pollination.

Lentil

By the Bronze Age, lentil had spread throughout the Mediterranean region and into both Asia and Europe. Lentil was used by the ancient Greeks for soup and a

kind of bread. Pliny the Elder recorded how the plant grows and noted its therapeutic qualities as well. Lentil is currently an important crop throughout the Mediterranean region, Western Asia and North America (Erskine, 1997), with Canada being the largest producer (FAOSTAT, 2016). Lentil production in Europe in 2013 was 70,000 t, 59% of which were harvested in Spain. It is a food crop, as yields are too low and production costs too high for it to be used as feed. It is considered sensitive to waterlogging, and grows best on well-drained mineral soils in regions with dry autumns.

Seed size varies widely, from 30 mg to 70 mg, and large-seeded cultivars tend to be later maturing than small-seeded ones. Small-seeded cultivars (< 45 mg) are sometimes called *microsperma* or Persian, and large-seeded ones *macrosperma* or Chilean, but the distinction is artificial and seed size is continuously variable rather than bimodal. The plant is relatively short (often only 40 cm tall), and more highly branched than pea or faba bean. The leaves produced from reproductive maturity onwards end in small tendrils that tie the plant stand together. Short racemes bearing one to three flowers are borne in the leaf axils, usually starting at node 11–14. The small flowers are reliably self-pollinating and produce pods with one to two seeds each. In order to bring the indeterminate growth to an end and allow maturity and harvesting, some farmers in Canada apply a desiccant.

The pods hang close to the soil, so farmers are advised to have as even a soil surface as possible, and to set the cutter bar of the combine harvester low. The seeds are easily handled by conventional farm machinery that is set up to handle small-grain cereals such as wheat and barley.

Cultivars with red cotyledons are generally sold as decorticated, split cotyledons, so ease of dehulling is an important trait, whereas those with yellow cotyledons are generally sold whole and there is no need to select for dehulling ability.

In continental climates, lentil is spring sown and in Mediterranean climates, autumn sown. A reputedly winter-hardy cultivar, 'Morton', was developed at Washington State University in the USA and has survived some winters in the nemoral to boreal climates of Saskatchewan, Canada and southern Finland, but not reliably so.

Chickpea

Chickpea spread westwards from the Middle East to the countries around the Mediterranean and eastwards to India. In classical Greece it was called Erevinthos and was eaten as a main dish or as a green vegetable. The Romans ate it in soup or roasted as a snack, much like we have them today. Chickpea is grown on over 10 million ha, primarily in arid and semi-arid areas worldwide (FAOSTAT, 2016). It is second to common bean in terms of spread and third in terms of production among the grain legumes. The major producer is India, with 65% of the world harvest, followed by Pakistan and Turkey. In Europe, the largest producer is Spain, producing 52% of the continent's 50,000 t.

The chickpea plant is similar to lentil, being relatively short (40–70 cm) and highly branched, with many leaflets per leaf. The leaves bear numerous glandular hairs and release oxalic and malic acids, so chickpea breeders are often

recognized by their holey trousers. After 12–14 vegetative nodes, the plant starts producing one (occasionally two) flowers per node, each of which produces one to two seeds. Like the other cultigens of the *Fabaeae*, chickpea has a wide range of seed sizes, from 120 mg to 600 mg, and two size classes are generally recognized, desi and kabuli. Desi chickpeas are relatively round-seeded, < 300 mg in size, with a coloured (tannin-containing) seed coat and coloured (pink) flowers, and are generally used for split cotyledons. Kabuli chickpeas have a characteristic ‘ram’s-head’ shape and are > 260 mg in size, with a thin and colourless seed coat and colourless (white) flowers, and are generally cooked whole. The kabuli seed coat is relatively thin and easily damaged during harvest, and the seeds are less tolerant of cold soils at germination time in comparison with desi seeds.

Like lentil, chickpea is spring sown in continental climates and in autumn in Mediterranean areas. The severity of its ascochyta blight restricted autumn sowing for many centuries, and it is only in recent decades with the advent of resistance breeding that autumn sowing has spread, inspired by successes in southern India (O’Toole *et al.*, 2001).

Lupins

Narrow-leafed lupin (*Lupinus angustifolius* L.), white lupin (*Lupinus albus* L.) and yellow lupin (*Lupinus luteus* L.) all originated in the Mediterranean Basin. Owing to their high alkaloid content, lupin seeds had to be washed in running water for up to 2 days before consumption, until low-alkaloid germplasm was developed in the 20th century, largely through mutation breeding. The domestication of these still half-wild crops was driven particularly in Western Australia from the 1950s. The Andean ‘tarwi’ or pearl lupin (*Lupinus mutabilis* Sweet) is evolutionarily remote from the Mediterranean species and was domesticated in middle altitudes along the central Andes of South America. Total European production of domesticated lupins was 151,000 t in 2013, two-thirds of which was grown in Poland (Eurostat, 2016). The lupins form symbiosis with a rhizobium that has not been taxonomically characterized and is usually called *Bradyrhizobium ‘lupini’*. Lupins are covered in greater detail in this volume by Gresta *et al.* (see Chapter 6, this volume).

Typical target seedling rates are 50–70/m² for white lupin, and 120–140/m² for narrow-leafed and yellow lupin. Lupin germination is epigeal, bringing the cotyledons and cotyledonary buds above ground, so the seedlings may be killed by physical damage during crop management that would only set back hypogeal germinating species. The leaves are palmately compound with long and narrow leaflets held almost at right angles to the petiole. After several nodes of vegetative growth, the main stem produces some axillary flowers and develops into a spike with whorls of flowers. The axils of the last two to four leaves then produce branches that repeat the growth pattern of the main stem, subsequently producing another order of branches. In some growing conditions, up to five orders of branches may be produced. For cropping purposes, however, reduced branching is desirable in order to bring the crop to maturity and harvest readiness.

Non-branching cultivars have been produced in narrow-leaved lupin, reducing the growing season to a length that allows the crop to be grown up to 63°N in Finland, but biomass production and seed yields are low. Reduced- or non-branching cultivars have been developed in both yellow and white lupin cultivars, with similar detriment to yield potential. Non-branching cultivars cover the ground poorly, so they have little ability to suppress weed growth, and they require high sowing densities. Thus a balance is required, and it may be that a reduced-branching cultivar, rather than non-branching, will provide the best combination of sowing density, ground coverage and maturity date for all but the most extreme climates.

Like faba bean, lupins produce far more flowers than can mature as pods. Narrow-leaved and yellow lupins self-pollinate in the bud, but are still attractive to pollen-collecting bees. White lupin self-pollinates shortly before anthesis, and its outcrossing rate is higher than those of the other two. It is generally acknowledged that these three species have no detectable nectar. Each flower contains four to five ovules. Seed size is less variable than in some of the other grain legumes, with most white lupins being around 300–320 mg, Andean 200 mg, narrow-leaved 140–170 mg and yellow 130–140 mg.

The agricultural lupins are adapted to acid, sandy soils and are exceptionally sensitive to waterlogging and free calcium, although there has been some success in breeding calcium-tolerant germplasm. Winter-hardy cultivars of white lupin have been developed for the oceanic regions of France by the Jouffray-Drillaud company.

Lupin seed composition is radically different from those of the other legumes. There is significant oil content, averaging about 6% in narrow-leaved and yellow (Sujak *et al.*, 2006; Lizarazo *et al.*, 2015), 10% in white (Annicchiarico *et al.*, 2014) and 15% in Andean (Carvalho *et al.*, 2005). The main form of energy storage is beta-galactan, a complex polysaccharide deposited in the heavily thickened cell walls of the cotyledons. Seed protein content is about 32% in narrow-leaved lupin, 35% in white lupin, 40% in Andean lupin (Clements *et al.*, 2008) and 45% in yellow lupin (Sujak *et al.*, 2006). The seed coat is relatively thick, and the protein content of dehulled cotyledons is several per cent higher than these values. The amino acid composition of yellow lupin has been claimed to be superior to that of soybean (Hudson, 1979).

The main restricting factor in lupin usage is quinolizidine alkaloids that are up to 2% of the dry matter of landraces. These are highly diverse chemicals and their profile differs in each species. The alkaloids are synthesized throughout the plant and transported to the seed, so the development of a lupin with sweet seeds but bitter leaves that protect it from herbivores would depend on the identification and silencing of a still unknown alkaloid transporter (see Chapter 6, this volume). In several countries, including the UK and France, the maximum alkaloid content in lupin seeds for food and feed use is 200 mg/kg, and most current cultivars are below this level.

The main limiting disease is anthracnose, caused by *Colletotrichum lupini*. Phomopsis, a mycotoxin produced by *Diaporthe toxica*, causes poisoning of ruminants grazing lupin residues. There is a large literature on diseases of lupins caused by *Fusarium* species. The same aphids and leaf

weevils attack lupins as *Fabeae* legumes, along with two European specialist *Sitona* species, *S. gressorius* and *S. griseus*. Alkaloid content appeared not to affect attractiveness to leaf weevils (Strocker *et al.*, 2013), but alkaloid composition affected aphid infestation, indicating that there is potential for combining low overall alkaloid content and aphid resistance (Adhikari *et al.*, 2012).

The Warm-season Legumes

The warm-season legumes in the *Phaseoleae* have numerous distinctions from the crops described so far. The natural habit of the wild species is generally vining, not clasping with tendrils. There is little frost hardiness in most species, and the optimum growing temperature is above 24°C. Seedling emergence is epigeal, so the cotyledonary buds are susceptible to damage. The leaves are trifoliolate, and the leaflets are heart-shaped. As is typical of tropical and subtropical species, flowering in warm-season legumes requires days that are shortening and below a critical length in order to flower. At medium to high latitudes, these shorter days are not reached until too late in the growing season, so selection by farmers and breeders has gradually changed the critical photoperiod. Insensitivity to photoperiod has been identified in common bean and a major gene conferring this trait, *Ppd*, has been identified (Gu *et al.*, 1998), but more than one gene is required in soybean (Xu *et al.*, 2013). Racemes are borne in the leaf axils after a certain number of vegetative nodes, as in the *Fabeae*. The flowers of common bean and soybean pollinate themselves before opening. The development of determinate cultivars has been important in the domestication of these crops, making them uniform in maturity and suitable for mechanical harvesting. Determinate cultivars produce several branches, whereas indeterminate ones branch more rarely. The usual seeding rate is 30–50/m² for both species, depending on soil type, maturity group and branching pattern.

Common bean

Common bean comes from the Americas, with apparently independent domestication events around 4000 BC in Mexico, Colombia and Bolivia (Barker, 2006). It was brought to Europe shortly after the first European contact at the end of the 15th century, and gradually, through the trade of the Spanish and the Portuguese, it spread to Africa and Asia. The spread of common bean in Europe was complex, with several introductions from the New World combined with direct exchanges between European and other Mediterranean countries (Angioi *et al.*, 2010). Most European landraces of common bean are from the Andean gene pool, with minor differences across European regions in the proportions of the Andean and Mesoamerican gene pools. Recombinant forms between both genetic pools have been described from Europe, which is considered a secondary area of domestication of the species (Santalla *et al.*, 2002). Europe produced 245,000 t of dry bean

in 2013, and Serbia was the largest producer (Fig. 5.3). FAOSTAT (2016) showed world production as 23 million t in 2013, making it by far the most-produced grain legume after soybean, but this value included some other *Phaseolus* and *Vigna* species.

Seed size in common bean ranges from at least 170 mg to 1000 mg. Seed-coat colour is highly variable, and there are cultural preferences for colour and seed size in many regions of the Americas. It is considered a food crop and is seldom used for feed, owing to its high cost and the presence of phytohaemagglutinins that require denaturing by cooking before monogastrics can consume them. Each pod contains up to eight seeds, and the long pods often reach the soil surface and are liable to rot, so plant height and an upright growth habit have been important breeding objectives. The fresh pods without fibre can be consumed as snap beans. The seed coat is very thin and is easily damaged during sowing and harvest, leading to poor viability.

Common bean is highly sensitive to frost at all growing stages, and requires warm soils for germination. It is also sensitive to water deficit, waterlogging and salinity. It is notoriously poor at nodulating and nitrogen fixation, and the causes and solutions have yet to be established. The most important diseases are due to the generalist fungus, *Sclerotinia sclerotiorum*, and the specialist bacteria that cause: (i) common blight, *Xanthomonas campestris* pv. *phaseoli*; (ii) halo blight, *Pseudomonas syringae* pv. *phaseolicola*; and (iii) bacterial brown spot, *Pseudomonas syringae* pv. *syringae*. Resistance breeding has made progress against the bacterial diseases, but not significantly against sclerotinia.

Soybean

Many authors and databases categorize soy as an oilseed, but taxonomically it is a legume, so it should be considered here. After the cereals maize, wheat and rice, it is the world's most widely grown grain crop, with 308 million t harvested in 2014 according to FAOSTAT (2016). Production in the EU in that year (Eurostat, 2016) was 1.85 million t, of which 50% was harvested in Italy. The European region as defined by Eurostat imported 27 million t of soymeal and 15 million t of soybeans. Production in countries neighbouring the EU is very significant with 3.9 million t and 2.6 million t produced in Ukraine and Russia, respectively (see Chapter 7, this volume).

The species is an ancient tetraploid, with the genome duplication estimated at 8 million years ago (Shoemaker *et al.*, 1996), which affects the practical breeding of the crop, as often two genes need to be altered in order to achieve a desired phenotype. Soybean is discussed at greater length in this book by Fogelberg and Recknagel (Chapter 7, this volume).

The oil content of soybean (around 20%) is lower than that of most other oilseeds, and the protein content (around 40%) is somewhat higher, so the oil-free meal is usually 45–50% protein. The amino acid composition of the meal is considered excellent for most feed and food purposes. Usage in food and feed is limited by two strong trypsin inhibitors, one a Bowman–Birk type and the other a Kunitz type, that require heat treatment for denaturation.

The strong photoperiod dependence of soybean has led to the development of numerous 'maturity groups' with narrow ($2\text{--}3^\circ$ of latitude) zones of adaptation in North America. Maturity groups 000 to 2 cover most of Europe's needs from the southern shore of the Baltic to the northern shore of the Mediterranean.

Seeds of modern cultivars of soybean are 150–250 mg in weight. The seed coat is usually yellow, but may be green, brown or black. Unlike most of the other legumes, soy is not considered to be restricted to certain soil types or pH values. The first two true leaves are unifoliolate, and thereafter trifoliolate leaves are produced. The first raceme is borne in the axil of the fifth to seventh trifoliolate leaf, and the racemes carry three to five flowers that pollinate themselves before anthesis. More flowers are produced than can mature, as in most other grain legumes. The pods contain three to four seeds. Indeterminate cultivars produce one to two stems, determinate ones two to six.

Although soybean has a reputation for being frost-tender, young plants of many cultivars can survive temperatures of -3°C . If the exposure to frost is short (an hour rather than overnight), and the seedling or young plant has been hardened by exposure to cool temperatures ($< 10^\circ$ for several days), then a substantial portion of the crop can survive -4°C (Badaruddin and Meyer, 2001).

Several rhizobia nodulate soybean, but two species predominate: (i) *Sinorhizobium fredii* on neutral to alkaline soils; and (ii) *Bradyrhizobium japonicum* on acid or saline soils (Tian *et al.*, 2012). Since these species are not widespread in Europe, it is necessary to inoculate soybeans before sowing the crop for the first time in a field.

Since it is grown on all inhabited continents, it is exposed to a wide range of diseases and pests, and the literature on crop protection is vast. In Europe, the main pathogens are *Peronospora manshurica* (downy mildew) and *Pseudomonas syringae* pv. *glycinea* (bacterial blight) on leaves, *Diaporthe phaseolorum* var. *caulivora* (canker) and sclerotinia on stems, and *Macrophomina phaseolina* (charcoal rot) on roots (Vidic and Jasnic, 2011). The range of pests is similarly wide, and includes the leaf weevils and aphids that attack the cool-season legumes (Sekulic and Keresi, 2011).

Conclusion

The grain legumes are diverse in taxonomy, seed composition and environmental requirements. This diversity means there is a potential legume crop for every arable field in Europe, but it has the disadvantage that breeding effort has to be spread across many species, and they cannot be easily substituted for each other in processes such as feed manufacture. With the rapid development and application of genomic technologies, these crops are no longer the 'orphans' that they were just 5 years ago (Sharpe *et al.*, 2013). Complete genome sequences are available for some and are in development for others, while the expressed portion alone (the exome) may be the target for large genomes such as that of faba bean. These technologies will allow information obtained in one species to be rapidly applied to the improvement of another. The breeding of legume crops is the subject of a new book (De Ron, 2015).

References

- Adhikari, K.N., Edwards, O.R., Wang, S., Ridsdill-Smith, T.J. and Buirchell, B. (2012) The role of alkaloids in conferring aphid resistance in yellow lupin (*Lupinus luteus* L.). *Crop and Pasture Science* 63, 444–451.
- Angioi, S.A., Rau, D., Attene, G., Nanni, L., Bellucci, E., Logozzo, G., Negri, V., Spagnoletti Zeuli, P.L. and Papa, R. (2010) Beans in Europe: origin and structure of the European landraces of *Phaseolus vulgaris* L. *Theoretical and Applied Genetics* 121, 829–843.
- Annicchiarico, P., Manunza, P., Arnoldi, A. and Boschini, G. (2014) Quality of *Lupinus albus* L. (white lupin) seed: extent of genotypic and environmental effects. *Journal of Agriculture and Food Chemistry* 62, 6539–6545.
- Badaruddin, M. and Meyer, D.W. (2001) Factors modifying tolerance of legume species. *Crop Science* 41, 1911–1916.
- Baddeley, J.A., Jones, S., Topp, C.F.E., Watson, C.A., Helming, J. and Stoddard, F.L. (2013) Biological nitrogen fixation (BNF) by legume crops in Europe. Legume Futures Report 1.5. Available at: www.legumefutures.de (accessed 4 April 2016).
- Barker, G. (2006) *The Agricultural Revolution in Prehistory*. Oxford University Press, Oxford, 598 pp.
- Bhattacharyya, M.K., Smith, A.M., Ellis, T.H.N., Hedley, C. and Martin, C. (1990) The wrinkled-seed character of pea described by Mendel is caused by a transposon-like insertion in a gene encoding starch-branching enzyme. *Cell* 60, 115–122.
- Carvalho, I.S., Chaves, M. and Ricardo, C.P. (2005) Influence of water stress on the chemical composition of seeds of two lupins (*Lupinus albus* and *Lupinus mutabilis*). *Journal of Agronomy and Crop Science* 191, 95–98.
- Clements, J.C., Sweetingham, M.S., Smith, L., Francis, G., Thomas, G. and Sipsas, S. (2008) Crop improvement in *Lupinus mutabilis* for Australian agriculture – progress and prospects. In: *Lupins for Health and Wealth. Proceedings of the 12th International Lupin Conference*, Fremantle, Western Australia, 14–18 September 2008, pp. 244–250.
- Crépon, K., Marget, P., Peyronnet, C., Carrouée, B., Arese, P. and Duc, G. (2010) Nutritional value of faba bean (*Vicia faba* L.) seeds for feed and food. *Field Crops Research* 115, 329–339.
- De Ron, A.M. (ed.) (2015) *Handbook of Plant Breeding: Grain Legumes*. Springer Science+Business Media, New York, 438 pp.
- Erskine, W. (1997) Lessons for breeders from landraces of lentil. *Euphytica* 93, 107–112.
- Eurostat (2016) Eurostat. European Commission, Brussels. Available at: <http://ec.europa.eu/eurostat> (accessed 4 June 2016).
- Evans, L.T. (1998) *Feeding the Ten Billion*. Cambridge University Press, Cambridge, 246 pp.
- FAOSTAT (2016) Statistics Database of the Food and Agriculture Organization of the United Nations, Rome. Available at: <http://faostat3.fao.org/home/E> (accessed 4 June 2016).
- Gepts, P. (2004) Domestication as a long-term selection experiment. *Plant Breeding Reviews* 24, 1–44.
- Graham, P.H. and Vance, C.P. (2003) Legumes. Importance and constraints to greater use. *Plant Physiology* 131, 872–877.
- Grusak, M.A. (2002) Enhancing mineral content in plant food products. *Journal of the American College of Nutrition* 21, 178S–183S.
- Gu, W., Zhu, J., Wallace, D.H., Singh, S.P. and Weeden, N.F. (1998) Analysis of genes controlling photoperiod sensitivity in common bean using DNA markers. *Euphytica* 102, 125–132.
- Gupta, Y.P. (1987) Anti-nutritional and toxic factors in food legumes: a review. *Plant Foods for Human Nutrition* 37, 201–228.
- Hudson, B.J.F. (1979) The nutritional quality of lupinseed. *Plant Foods for Human Nutrition* 29, 245–251.

- Jenkins, D.J.A., Kendall, C.W.C., Marchie, A., Jenkins, A.L., Augustin, L.S.A., Ludwig, D.S., Barnard, N.D. and Anderson, J.W. (2003) Type 2 diabetes and the vegetarian diet. *American Journal of Clinical Nutrition* 78, 610S–616S.
- Khamassi, K., Jeddi, F.B., Hobbs, D., Irigoyen, J., Stoddard, F.L., O'Sullivan, D.M. and Jones, H. (2013) A baseline study of vicine-convicine levels in faba bean (*Vicia faba* L.) germplasm. *Plant Genetic Resources: Characterization and Utilization* 11, 250–257.
- Kjaergaard, T. (2003) A plant that changed the world: the rise and fall of clover 1000–2000. *Landscape Research* 28, 41–49.
- Lee, J.M., Grant, D., Vallejos, C.E. and Shoemaker, R.C. (2001) Genome organization in dicots. II. *Arabidopsis* as a 'bridging species' to resolve genome evolution events among legumes. *Theoretical and Applied Genetics* 103, 765–773.
- Legumes of the World Online (LOWO) (2013) Legumes of the World Online. Board of Trustees of the Royal Botanic Gardens, Kew, London. Available at: <http://www.kew.org/science-conservation/research-data/resources/legumes-of-the-world> (accessed 1 August 2015).
- Link, W., Balko, C. and Stoddard, F.L. (2010) Winter hardiness in faba bean: physiology and breeding. *Field Crops Research* 115, 287–296.
- Lizarazo, C.I., Lampi, A.-M., Liu, J., Sontag-Strohm, T., Piironen, V. and Stoddard, F.L. (2015) Nutritive quality and protein production from grain legumes in a boreal climate. *Journal of the Science of Food and Agriculture* 95, 2053–2064.
- Madar, Z. and Stark, A.H. (2002) New legume sources as therapeutic agents. *British Journal of Nutrition* 88, S287–S292.
- Moussart, A., Even, M.N., Lesne, A. and Tivoli, B. (2013) Successive legumes tested in a greenhouse crop rotation experiment modify the inoculum potential of soils naturally infested by *Aphanomyces euteiches*. *Plant Pathology* 62, 545–551.
- Ndakidemi, P.A. and Dakora, F.D. (2003) Review: legume seed flavonoids and nitrogenous metabolites as signals and protectants in early seedling development. *Functional Plant Biology* 30, 729–745.
- O'Toole, N.A., Stoddard, F.L. and O'Brien, L. (2001) Screening of chickpeas for adaptation to autumn sowing. *Journal of Agronomy and Crop Science* 186, 193–208.
- Patrick, J.W. and Stoddard, F.L. (2010) Physiology of flowering and grain filling in faba bean. *Field Crops Research* 115, 234–242.
- Rubiales, D., Alcantara, C. and Sillero, J.C. (2004) Variation in resistance to *Orobanche crenata* in species of *Cicer*. *Weed Research* 44, 27–32.
- Santalla, M., Rodiño, A.P. and De Ron, A.M. (2002) Allozyme evidence supporting southwestern Europe as a secondary center of genetic diversity for common bean. *Theoretical and Applied Genetics* 104, 934–944.
- Sekulic, R. and Keresi, T. (2011) Pests of soybean. In: Miladinovic, J., Hrustic, M. and Vidic, M (eds) *Soybean*. Institute of Field and Vegetable Crops, Novi Sad, Serbia, pp. 446–497.
- Sharpe, A.G., Ramsay, L., Sanderson, L.-A., Fedoruk, M.J., Clarke, W.E., Li, R., Kagale, S., Vijayan, P., Vandenberg, A. and Bett, K.E. (2013) Ancient orphan crop joins modern era: gene-based SNP discovery and mapping in lentil. *BMC Genomics* 14, 192.
- Shoemaker, R.C., Polzin, K.C., Labate, J., Specht, J.E., Brummer, E.C., Olson, T., Young, N., Concibido, V., Wilcox, J., Tanmulonis, J.P., Kockert, G. and Boerma, H.R. (1996) Genome duplication in soybean (*Glycine* subgenus soja). *Genetics* 144, 329–338.
- Spergel, J.M. and Fiedler, J.M. (2001) Natural history of peanut allergy. *Current Opinion in Pediatrics* 13, 517–522.
- Stoddard, F.L. (2004) Starch chemistry. In: Wrigley, C., Corke, H. and Walker, C.E. (eds) *Encyclopaedia of Grain Science and Technology*. Elsevier, Amsterdam, pp. 213–219.
- Stoddard, F.L. and Bond, D.A. (1987) The pollination requirements of the faba bean (*Vicia faba* L.). *Bee World* 68, 144–152.

- Stoddard, F.L., Balko, C., Erskine, W., Khan, H.R., Link, W. and Sarker, A. (2006) Screening techniques and sources of resistance to abiotic stresses in cool season food legumes. *Euphytica* 147, 167–186.
- Stoddard, F.L., Nicholas, A.H., Rubiales, D., Thomas, J. and Villegas-Fernández, A.M. (2010) Integrated pest management in faba bean. *Field Crops Research* 115, 308–318.
- Strocker, K., Wendt, S., Kirchner, W.H. and Struck, C. (2013) Feeding preferences of the weevils *Sitona gressorius* and *Sitona griseus* on different lupin genotypes and the role of alkaloids. *Arthropod–Plant Interactions* 7, 579–589.
- Sujak, A., Kotlarz, A. and Strobel, W. (2006) Compositional and nutritional evaluation of several lupin seeds. *Food Chemistry* 98, 711–719.
- Tanno, K.-I. and Willcox, G. (2006) The origins of cultivation of *Cicer arietinum* L. and *Vicia faba* L.: early finds from Tell el-Kerkh, north-west Syria, late 10th millennium BP. *Vegetation History and Archaeobotany* 15, 197–204.
- Tian, C., Zhou, Y., Zhang, Y., Li, Q., Zhang, Y., Li, D., Wang, S., Wang, J., Gilbert, L., Li, Y. and Chen, W. (2012) Comparative genomics of rhizobia nodulating soybean suggests extensive recruitment of lineage-specific genes in adaptations. *Proceedings of the National Academy of Sciences of the USA* 109, 8629–8634.
- Tivoli, B., Baranger, A., Avila, C.M., Banniza, S., Barbetti, M., Chen, W., Davidson, J., Lindeck, K., Kharrat, M., Rubiales, D., Sadiki, M., Sillero, J.C., Sweetingham, M. and Muehlbauer, F.J. (2006) Screening techniques and sources of resistance to foliar diseases caused by major necrotrophic fungi in grain legumes. *Euphytica* 147, 223–253.
- Vidic, M. and Jasnic, S. (2011) Soybean diseases. In: Miladinovic, J., Hrustic, M. and Vidic, M (eds) *Soybean*. Institute of Field and Vegetable Crops, Novi Sad, Serbia, pp. 364–445.
- Wang, T.L., Domoney, C., Hedley, C.L., Casey, R. and Grusak, M.A. (2003) Can we improve the nutritional quality of legume seeds? *Plant Physiology* 131, 886–891.
- Wojciechowski, M.F., Lavin, M. and Sanderson, M.J. (2004) A phylogeny of legumes (Leguminosae) based on analyses of the plastid *matK* gene resolves many well-supported subclades within the family. *American Journal of Botany* 91, 1846–1862.
- Xu, M., Xu, Z., Liu, B., Kong, F., Tsubokura, Y., Watanabe, S., Xia, Z., Harada, K., Kanazawa, A., Yamada, T. and Abe, J. (2013) Genetic variation in four maturity genes affects photo-period insensitivity and PHYA-regulated post-flowering responses of soybean. *BMC Plant Biology* 13, 91.
- Zohary, D. and Hopf, M. (2000) *Domestication of Plants in the Old World*, 3rd edn. Oxford University Press, Oxford, 316 pp.

6

Lupins in European Cropping Systems

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Abstract

The lupins are an interesting group of legume crop species that produce large seeds containing up to 40% protein. The genus *Lupinus* is part of the tribe *Genisteeae*. More than 170 species have been described from the New World and only 12 species from Europe, North and East Africa. Wild lupins are bitter and toxic because they produce quinolizidine alkaloids as a means of chemical defence. During domestication, lupins with low alkaloid contents were selected, leading to 'sweet' lupins with alkaloid contents below 0.02% in the protein-rich seeds, which can be used both for human and animal consumption. The domesticated lupins include *Lupinus angustifolius*, *Lupinus albus*, *Lupinus luteus* and *Lupinus mutabilis*. Blue or narrow-leaved lupin (*L. angustifolius*) is the most widely cultivated of them, with a worldwide production of more than 1.3 million t. Several challenges remain for lupin breeding, including the improvement of quantitative and qualitative traits, adaptation to alkaline soil and resistance to fungal pathogens.

Introduction and Taxonomy

Lupin species from the Americas are mostly herbaceous perennials, whereas Old World lupins are generally annuals. All of them host symbiotic nitrogen-fixing *Bradyrhizobium* in root nodules (Sprent and McKey, 1994). Most lupins are 0.3–1.5 m tall; some shrubs reach 3 m in height and a few Andean species grow as trees. Lupin leaves are usually palmately compound, soft and divided into five to 28 leaflets, but a few species in south-eastern North America and Atlantic

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South America carry single leaflets. Flowers appear in dense or open whorls on an erect stem. The pea-like flowers (length 1–2 cm) consist of an upper standard, two lateral wings and a keel (formed from two fused petals). Fruits appear as a typical pod with several hard-coated seeds. Seeds are rather big (in agricultural species), with up to 40% protein, up to 20% lipid, fibre and several secondary metabolites (quinolizidine alkaloids (QA), flavonoids, isoflavones, tannins, saponins, oligo-saccharides). The fatty acid profile, particularly the polyunsaturated fatty acids (PUFAs) and n-3:n-6 PUFA ratio (Chiofalo *et al.*, 2012) is considered beneficial for human health (Boschin *et al.*, 2007) and in animal nutrition (Singh *et al.*, 1995; Vicenti *et al.*, 2009). In addition, lupin has been studied as a human foodstuff because of its potential in functional and healthy food products due to its hypo-cholesterolaemic and antidiabetic potential (El-Adawy *et al.*, 2001; Duranti *et al.*, 2008). Lupins are also cultivated as attractive ornamentals (e.g. Russell hybrids of *Lupinus polyphyllus* and other American species).

Lupinus is a large genus including about 170 species all over the world, only 12 of which are native in Europe or in the Mediterranean Basin: *Lupinus albus*, *Lupinus anatolicus*, *Lupinus angustifolius*, *Lupinus atlanticus*, *Lupinus cosentinii*, *Lupinus digitatus*, *Lupinus hispanicus*, *Lupinus luteus*, *Lupinus micranthus*, *Lupinus pilosus*, *Lupinus palaestinus* and *Lupinus princei* (taxonomy according to GRIN, 2013). Only four species are domesticated and play an important role in agriculture: three come from the 'Old World', *L. albus* (white lupin), *L. angustifolius* (narrow-leafed lupin) and *L. luteus* (yellow lupin); and one comes from the 'New World', *Lupinus mutabilis* (tarwi). Many other lupin species such as *L. cosentinii*, *L. pilosus* and *L. hispanicus* that are underutilized show potential as cultivated plants. Chromosome numbers range from $2n = 32, 36, 38, 40, 42, 50$ and 52 in Old World lupins to a more consistent number $2n = 48$ or 36 in New World lupins (Käss and Wink, 1997a).

Lupins very likely evolved in the Old World and colonized the Americas via long-distance dispersal almost 15 million years ago. Analysis of DNA sequences (Käss and Wink, 1997a, b; Hughes and Eastwood, 2006; Eastwood *et al.*, 2008) have revealed that three main phylogenetic lineages exist within lupins: (i) lupins of the Old World inhabiting the Mediterranean and African region north of the Sahara (approximately 12 species); (ii) lupins of North, Central and South America (approximately 130 species, depending on the authority) with a recent radiation that was induced by the uplift of the Andes and Rocky Mountains; and (iii) lupins of Atlantic South America (mainly Brazil) (approximately 30 species). A few North American lupins, such as *Lupinus texensis* cluster with Old World lupins. The relationships shown in Fig. 6.1 are important for lupin breeders as they explain why it is impossible or difficult to hybridize Old World lupin species with New World taxa. Hybrids are possible within the North American lupins and between *L. mutabilis* and *L. polyphyllus*.

The word 'lupin' derives from the Latin *lupus* (wolf) with different interpretations: able to grow in very hard environments or able to catch great quantities of nutrient from soil. The oldest record of *L. albus* dates back to around 3500 years BC, in the Late Neolithic, even if without specific evidence of cultivation. Later, clearer evidence of cultivated lupin has been found in the Bronze Age in Greece, Cyprus and Egypt. Seeds of domesticated *L. digitatus* were discovered in

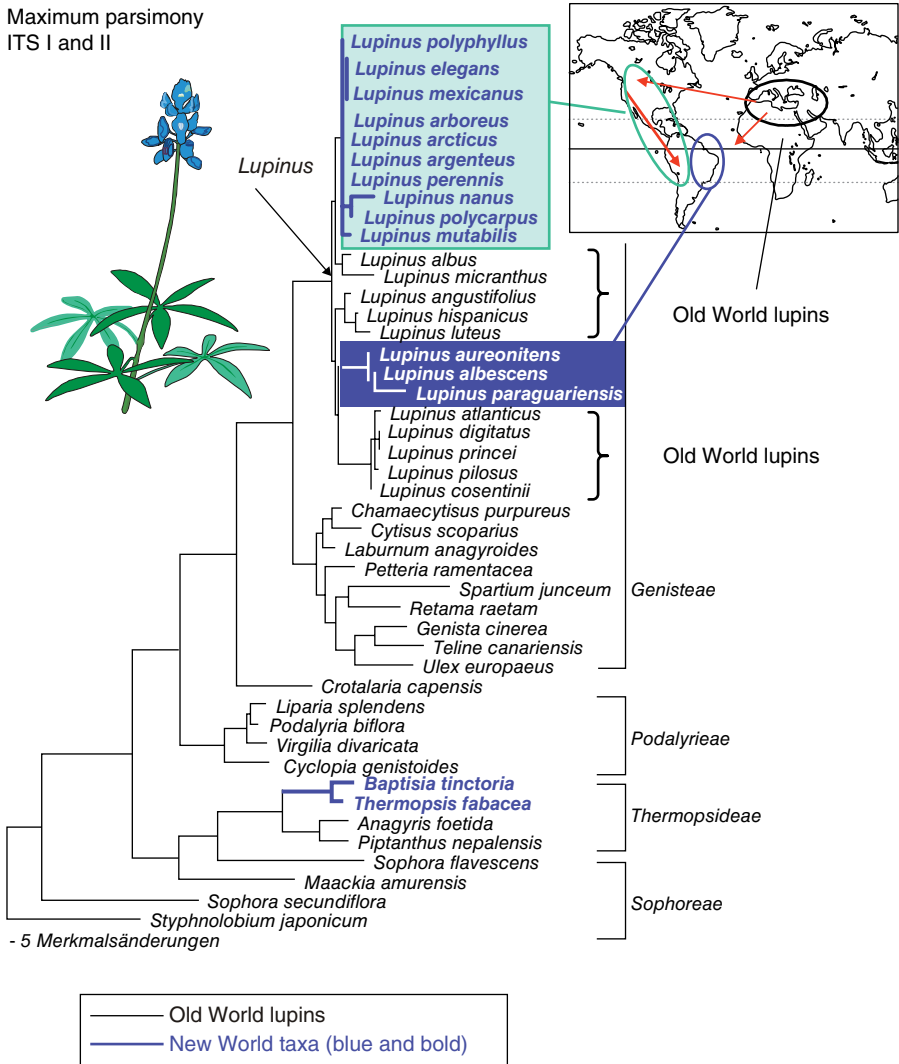


Fig. 6.1. Molecular phylogeny of *Lupinus* in relation to other legumes and to its geographic origin. ITS, Internal transcribed spacer.

the tombs of Pharaohs being over 4000 years old (Zohary *et al.*, 2012). *L. albus* was first cultivated as green manure, as forage and probably also for human consumption.

Cultivation became more widespread when people recognized that the bitter taste due to alkaloids could be removed by a prolonged soaking. Lupin is still a neglected crop species with only about 650,000 ha of cultivated lupins grown (FAOSTAT, 2014). Lupins account for about 1% of all the ten Food and Agriculture Organization of the United Nations (FAO)-recognized grain legume crops, grown largely on land not suitable for beans, chickpea, cowpea, pea, etc. In Europe, lupins are grown on about 150,000 ha, and the area is stable. Poland, the Russian

Federation, Germany, Belarus and Ukraine are the countries in which lupins are cultivated on more than 10,000 ha (FAOSTAT, 2014). In Germany, *L. angustifolius* is the main species grown, while in Poland both *L. angustifolius* and *L. luteus* are cultivated. The main production areas for *L. albus* are found in the south with Italy, France and Spain as the main lupin-producing countries (5000 ha, 3600 ha and 3045 ha, respectively, in 2013; FAOSTAT, 2014).

The main hindrance to the spread of lupins as a crop is low yield, low tolerance to alkaline soil, bitter and toxic alkaloids and anthracnose. Most of these obstacles have been addressed. Considering the low investment, great progress has been achieved in a short period of time.

Secondary Metabolites: Quinolizidine Alkaloids (QA)

Wild lupins are quite toxic due to QA (Wink, 1993) synthesized in the leaves which can account for up to 8% of their dry weight. If a lupin plant is wounded, its alkaloid content can be increased by a factor of four within a couple of hours (Wink, 1992, 1993). Lupins grown at high altitudes usually show lower alkaloid contents than those grown at lower elevations.

It has been postulated that the transfer from the phloem into the growing seeds also requires an alkaloid transporter, providing opportunities to breed lupins with high alkaloid levels in the green parts (to protect against herbivores) but low levels in the seeds. Another important group of secondary metabolites in lupins is the isoflavones, such as genistein, which bind to oestrogen receptors and can be regarded as phyto-oestrogens, a property that might be interesting for nutraceuticals (used to treat menopausal conditions and osteoporosis). Isoflavones also exhibit antifungal activities.

Properties and Uses

In recent years, legumes have established a key position for food and pharmaceutical industries not only for their nutritional role, but also for a number of both adverse and beneficial effects that they may exert on the human body, including food intolerance, allergies and hypolipidemic, hypoglycaemic, hypotensive and anti-obesity activities. In addition, lupin proteins can play important techno/functional roles as witnessed by their increased uses as food ingredients.

Lupin seeds contain two main classes of proteins. These are the albumin and globulin fractions, which account for 10% and 90% of the total protein content, respectively (Blagrove and Gillespie, 1975; Duranti *et al.*, 1981). Prolamins and glutelins are absent.

The most representative albumin protein is δ -conglutin that belongs to the 2S sulfur-rich albumin family (Blagrove and Gillespie, 1975) and accounts for about 5% of the total seed proteins. It is structurally related to cereal bifunctional trypsin/ α -amylase inhibitors (Gourinath *et al.*, 2000). The interest in this protein

lies in the physiological role, being involved in plant defence against pathogens (Terras *et al.*, 1992; Agizzio *et al.*, 2003).

Three different proteins fall within the globulin group. α -Conglutin belongs to the 11S globulin family (legumin-like) and represents about 35–37% of the total globulins (Duranti *et al.*, 1981). β -Conglutin belongs to the 7S globulin family (vicilin-like) and is the most abundant protein in the seed (about 44–45%) (Duranti *et al.*, 1981). γ -Conglutin is an unusual basic 7S glycoprotein, which accounts for about 4–5% of total proteins in mature lupin seeds (Duranti *et al.*, 1981) and is likely to be involved in plant defence mechanisms (Scarafoni *et al.*, 2010).

From a nutritional point of view, lupin seed proteins have a biological value of about 90% that of egg protein (Egaña *et al.*, 1992). White lupin seeds have a higher essential amino acid index and protein efficiency ratio than narrow-leaved and yellow lupins (Duranti *et al.*, 2008).

Lupin proteins can cause allergic reactions in individuals sensitized to peanut and other legume seeds (Moneret-Vautrin *et al.*, 1999; Parisot *et al.*, 2001). For these reasons, lupin has recently been added to the list of potential allergenic foods and its use as an ingredient should appear on the labelling of foodstuffs (European Commission Directive, 2006/142/ EC) as a precautionary measure for consumer protection.

Because of the low off-flavour, lupin flour and protein isolates are suitable for novel foods. A variety of lupin-based preparations is now available on the market: (i) tofu-like and tempe-like products; (ii) milk and meat product analogues; (iii) bakery products; and (iv) gluten-free pasta, sauces, mayonnaise and salad dressings.

Lupin flours may be used as ingredients in bakery products with up to 20% of inclusion (Dervas *et al.*, 1999; Pollard *et al.*, 2002; Sironi *et al.*, 2005). The use of lupin flour promotes water retention and fat binding in dough and is also considered an excellent egg and butter replacement. Since lupin does not contain gluten, lupin flour is used as a functional ingredient in gluten-free foods (Capraro *et al.*, 2008). Partially purified lupin protein fractions are commercially available (Wäsche *et al.*, 2001).

Beyond the nutritional and technological aspects, lupin is a good source of bioactive compounds, opening up opportunities for new food products. Several molecules, such as proteins, peptides and smaller molecules such as alkaloids, isoflavones and oligosaccharides, isolated from seeds of common and uncommon legume plants have already been investigated for their bioactivities (Scarafoni *et al.*, 2007). The search for novel activities is expanding. Several biological activities have been attributed to the protein fraction, particularly to γ -conglutins. These include glycaemia (Magni *et al.*, 2004; Terruzzi *et al.*, 2011), plasma cholesterol/triglyceride lowering effects (Sirtori *et al.*, 2004) and anti-hypertensive properties (Yoshie-Stark *et al.*, 2004; Pilvi *et al.*, 2006).

The average oil content amounts ranges from 5% to 6% in *L. angustifolius* and *L. luteus* to about 15–17% in *L. mutabilis*. *L. albus* shows intermediate oil content (9–13%) (Chiofalo *et al.*, 2012). The growing environment (location, time of sowing, climatic variations) affects lipid accumulation, fatty acid quality and phytosterol composition, protein content and composition (Annicchiarico *et al.*, 2014). Lupin oil has a higher omega-3:omega-6 ratio than reported for most

vegetable oils (Boschin *et al.*, 2007). All of this makes lupin oil potentially valuable in dietary uses.

The fibre fraction is also relevant. The content of total dietary fibre (TDF) and insoluble dietary fibre (IDF) is considerably higher than in other legumes, including soybean, but soluble dietary fibre (SDF) is slightly lower (Pisarikova and Zraly, 2010).

These qualitative traits offer novel business opportunities. Improving knowledge on seed components and their properties is crucial for their optimal exploitation and to develop new products for the food and non-food industries. Proteins seemingly have the greatest potential to be exploited in this respect, owing to the diverse biological activities of their peptides. The potential for use of the lipids is underestimated, possibly because their limited quantities do not encourage industrial extractions and applications. The moderate oil content of white lupin may justify selection work aimed to further increase this characteristic offering the prospect of a dual purpose protein and oil crop like soy.

Genetic Resources, Genomic Tools and Breeding

Ex situ genetic resources

A key aspect underpinning current and future plant breeding efforts is the availability of appropriately conserved and documented germplasm (often referred to as plant genetic resources for food and agriculture, PGREFA).

Westengen *et al.* (2013) provide information on lupin accessions recorded in key databases, namely: (i) the gene bank-level data in the FAO World Information and Early Warning System (WIEWS) on PGREFA; and (ii) accession-level data in GENESYS (a database with information on over 2.3 million accessions from 365 gene banks). For *Lupinus* they found 38,053 reports in WIEWS but only 7503 of these are estimated to represent distinct accessions. Westengen *et al.* (2013) also reported 13,567 accessions in GENESYS. In the Svalbard Global Seed Vault (SGSV) they record a current holding of 591 accessions. The major gene bank holdings of *Lupinus* are in Australia, Germany, Peru, Russia, France and the UK.

The Australian collection holds a significant number of accessions of the major cultivated species (*L. albus*, *L. angustifolius* and *L. luteus*) but also smaller numbers of important related species (e.g. *L. cosentinii*, *L. pilosus* and *L. mutabilis*). None of this germplasm is currently held in the SGSV. Indeed *Lupinus*, as described by Westengen *et al.* (2013), is one of the important non-Annex 1 food crops for which the representation in SGSV is less than 10% of the distinct accessions shown in WIEWS.

The European Cooperative Programme for Plant Genetic Resources (ECPGR) is an important network for conservation and use of PGREFA. The ECPGR database is hosted at the Institute of Plant Genetics, Polish Academy of Sciences. For *L. albus* (3677 accessions listed), the major centres are the Institut National de la Recherche Agronomique (INRA) France, Spain (732 accessions), Germany, USA and Poland, with the biggest collection (979 accessions) in Australia at the Centre

for Legumes in Mediterranean Agriculture (CLIMA). A similar pattern is seen for *L. angustifolius* with 3894 accessions including 542 in Spain and 2165 at CLIMA. The listing shows a smaller number of accessions of *L. luteus*: 1799 with 463 at CLIMA and 303 in Spain.

Crop wild relatives or landraces are particularly useful as sources of disease resistance. Adhikari *et al.* (2009) described the situation in *L. albus* with respect to the use of landraces for the introduction of anthracnose resistance into modern cultivars.

Genetic and Genomic Tools

There is now a growing body of genetic and genomic resources available for lupin breeders to increase the speed and precision of their programmes. This is especially true for narrow-leaved lupin, whose genome sequencing is nearing completion in Australia.

Within the last 10 years, genetic maps of white and narrow-leaved lupins have been developed (Nelson *et al.*, 2006; Phan *et al.*, 2007). These studies have gained from work carried out on the model legumes *Medicago truncatula* and *Lotus japonicus* (Zhu *et al.*, 2005). Although lupins are somewhat more taxonomically remote from these models than the other important crop legumes, information on synteny (arrangement of genes on chromosomes) between lupins and these models is useful with respect to both marker and gene discovery. The genome sequencing of both these models opened up important possibilities with regard to alignment to help the sequencing of the lupin genome (Nelson *et al.*, 2010). Quantitative trait loci (QTL) were identified for anthracnose resistance and flowering time by Phan *et al.* (2007). White lupins were used by Croxford *et al.* (2008) to map sequence-tagged sites onto genetic maps using high-resolution melt analysis to identify the sites of sequence variation.

However, the limitations of approaches based only on QTL derived from biparental crosses have become clearer in recent years, so association mapping methods have become more popular. First, it is necessary to analyse the population structure of the species or accessions of that species that are to be used in the mapping. An estimate of the rate of decay of linkage disequilibrium is also required. Iqbal *et al.* (2012) carried out such a study for 122 accessions of white lupin. This work re-emphasizes the importance of *ex situ* collections and the documentation accompanying them.

Anthracnose, caused by the fungus *Colletotrichum lupini*, is the most devastating disease of lupin in most environments, so resistance to this disease has been a major breeding objective. Early flowering to avoid terminal drought is also important under these conditions, and the two traits were combined by Adhikari *et al.* (2013).

Next generation sequencing (NGS) approaches have been used to develop a draft genome sequence of *L. angustifolius* (Yang *et al.*, 2013b) using the high-yielding, anthracnose-resistant cultivar ‘Tanjil’. In addition, these authors developed a restriction-site associated DNA sequencing (RAD-seq) genetic map based on 94 F₈ recombinant inbred lines derived from a cross between ‘Unicrop’ and

'Tanjil'. As compared to a full genome analysis, RAD-seq data cover only part of the genome. NGS also facilitates the development of sequence-specific markers for key traits, with disease resistance genes again being the first exemplars (Yang *et al.*, 2010, 2012, 2013a). Transgenic resources have been developed for *Lupinus*, mostly focused on protein quality. The feasibility of this approach was shown by Molvig *et al.* (1997), who enhanced methionine levels in *L. angustifolius* through the expression of a sunflower seed albumin gene. This addresses the major issue of protein composition with respect to animal diets, namely the deficiency that lupins share with many other grain legumes with respect to the sulfur-containing amino acids cysteine and methionine. Further work showed that a similar approach can also increase the efficiency of wool growth and live-weight gain in sheep fed on such transgenic lupin seed (White *et al.*, 2001). The first report of the production of transgenic plants in *L. luteus* was made by Li *et al.* (2000), who used *Agrobacterium*-mediated transformation to introduce a gene for herbicide resistance. Disease resistance has also been a target for transgenic interventions. Wijayanto *et al.* (2009) reported the use of *Agrobacterium*-mediated transformation to introduce the baculovirus anti-apoptotic *p35* gene to combat fungal necrotrophs with some indications of potential for success. Hamblin *et al.* (2005) concluded that the likelihood of gene flow from a transgenic crop of *L. angustifolius* in Western Australia to wild lupin populations is extremely low, but the situation may differ where wild relatives occur.

Breeding

The history of lupin breeding in general (Cowling *et al.*, 1998), and in Australia specifically, has been reviewed (Cowling and Gladstones, 2000) and will not be repeated here.

An important part of the domestication of lupins has been the reduction of QA content, eliminating the bitterness and making the lupin seed palatable and safe for human consumption. Total seed alkaloid should remain under 0.02%. Nevertheless, alkaloids in lupins are responsible for resistance to herbivorous insects including aphids, which are a major pest and a limiting factor in the development of *L. luteus* as a crop. Adhikari *et al.* (2012) described approaches to the selection of lupin lines with diverse alkaloid profiles to form the basis of a breeding programme in this crop.

In Russia, breeding of *L. albus*, *L. angustifolius* and *L. luteus* draws on the genetic resources of the Vavilov Institute of Plant Industry collection (Lukashevich *et al.*, 2011). Again, anthracnose resistance is a major target along with yield, quality (protein and oil), early maturity and resistance to lodging. However, anthracnose is not the only significant fungal disease of lupin. A survey of soil-borne pathogens of narrow-leafed lupin in north-eastern Germany showed a range of species including *Fusarium* spp., *Rhizoctonia solani* and *Thielavopsis basicola* (Kaufmann *et al.*, 2011). The authors used nested PCR to identify fungal species and highlight the importance of developing robust resistance screens, particularly for *Fusarium oxysporum* and *T. basicola*.

The importance of root structure in nutrient use efficiency, tolerance of abiotic stress and carbon sequestration is becoming increasingly well documented. The modelling of root traits represents one approach to develop a basis for selection of desirable root characteristics from accessions or breeding lines. Chen *et al.* (2012) used *L. angustifolius* accessions with diversity characterized by DArT (Diversity Arrays Technology) to investigate variation in root traits in a semi-hydroponic phenotyping system.

Clearly, lupin species are currently minor crops in many countries and key constraints include unreliable yields, late maturity and poor tolerance of alkaline soils. A programme of breeding of lupins for adaptation to new environments and uses is required in countries where they have considerable potential but are not widely grown currently. Abberton and Mizen (2008) reported some first steps in this regard for the UK. Their major targets were increased yield, earlier flowering and improved tolerance of alkaline soils in *L. angustifolius* and *L. luteus*. Considerable progress was made after 3 years of phenotypic selection of individual plants, rows and plots. A hydroponic system was used to select for enhanced tolerance of alkaline pH and promising lines were identified. This indicates that even with a narrow range of germplasm, rapid progress can be made with respect to ecogeographic and edaphic adaptation. A further key component is quality for diverse uses including human food and aquaculture as well as an important source of protein in the ruminant diet.

Eickmeyer (2008) enumerated the following objectives for a private-sector breeding programme for narrow-leafed lupin in Germany:

- productivity – seed yield, raw protein yield, number of pods, number of seeds per pod, 1000-kernel weight;
- yield stability – frost tolerance, drought tolerance, lodging resistance, pod shattering resistance, flower dehiscence, soil pH tolerance, early ripening, equal ripening;
- disease resistance – *Colletotrichum*, soil-borne fungal pathogens, *Setoria* beetle; and
- seed quality – protein quality, antinutritive substances, alkaloids, fibre content and quality, phyto-oestrogens, oil quality.

This list shows the range of challenges for the lupin breeder and emphasizes the need for development in high-throughput phenotyping alongside advances in genomics.

Efforts in northern Europe have also focused on narrow-leafed lupin and its adaptations to a range of ecoclimatic conditions, since its growing season is shorter than those of the other domesticated species. Kurlovich *et al.* (2011) reported on the performance of 50 accessions grown across Finland, Russia and Ukraine and the development of cultivars for Finnish conditions.

The study of lupins has clearly advanced into the genomics era, but there is some way to go before the full suite of tools is applied effectively, alongside high-throughput precision phenotyping in breeding programmes, particularly for complex traits such as yield, yield stability and tolerance of edaphic stress. Successful improvement in these traits is necessary if lupins are to expand their role in crop production globally.

Canopy Structures

Domesticated lupin species usually have both branching and non-branching cultivars. As the non-branching cultivars flower only on the main stem, they ripen earlier and more uniformly than branching cultivars. In the latter, the number of branching (and hence flowering and pod-setting) levels is not only genetically determined, but also influenced by environmental and cropping conditions, such as plant density.

Adaptation: Climate and Soil

Of the Old World lupin species, yellow lupin (*L. luteus*) is generally the most drought-resistant and can be grown on the poorest soils with lowest pH (pH 4). However, due to its limited yield potential and high disease susceptibility, yellow lupin production and breeding in Europe is very limited.

Narrow-leaved lupin (*L. angustifolius*) generally requires a minimum soil pH of 5 and maximum pH of 6.5–6.8. It is the main lupin species grown in northern Europe. Non-branching cultivars of narrow-leaved lupin have shorter growing periods than branching cultivars (90–150 days versus 150–180 days), so they can be grown as far north as Finland, whereas branching cultivars are grown no further north than Denmark.

White lupin (*L. albus*) has somewhat wider adaptation to different soil types than the other species, growing also on loamy and light clay soils. Compared with other lupin species, its calcium tolerance can be relatively high, although this property seems to vary widely depending on the origin of the germplasm. Due to its long growing period (140–200 days) it is unsuitable for growing for seed further north than the Netherlands.

Calcium Tolerance

Most commercial cultivars of *L. angustifolius* and *L. luteus* grow poorly on calcareous soils, showing poor nodulation and high levels of chlorosis. Tang and Thomson (1996) suggested this to be the result of low tolerance of *Bradyrhizobium* to high soil pH (pH > 6). However, Nuijten and Prins (2013) successfully inoculated and grew white lupin on soils with pH 7.5 (CaCO₃ 8.6%). Other studies suggest that chlorosis in calcium-intolerant cultivars is due to reduced iron uptake (Coulombe *et al.*, 1984). However, Raza *et al.* (2001) found no significant differences in iron uptake between tolerant and intolerant *L. albus* cultivars. The latter study did find that intolerant cultivars took up significantly more calcium. High calcium levels in leaf tissue reduce the opening of stomata and hence reduce assimilation rates.

Calcium-tolerant cultivars have been found in *L. pilosus* (Brand *et al.*, 2000) and, within *L. albus*, in Egyptian (Christiansen *et al.*, 1999; Raza *et al.*, 2001) and Italian (Annicchiarico and Thami-Alami, 2012) landrace germplasm. Cultivars of white lupin have been grown successfully on soils with pH values of up to 7.8

and free calcium-carbonate levels of 6.5–8.6% (Gresta *et al.*, 2010; Nuijten and Prins, 2013). Some Egyptian landraces of white lupin are even able to grow on soils with pH values of 8.5 and higher, tolerating free calcium levels of over 10% (Christiansen *et al.*, 1999). On the other hand, there are reports of white lupin grain and biomass reduction already in the presence of soil-free calcium above 1% (Papineau and Huyghe, 2004), which indicates that calcium tolerance varies widely within the species.

The ability to form proteoid roots and excrete citric acid is thought to be one of the main mechanisms of calcium tolerance, as the acids reduce calcium uptake in favour of iron and phosphorus uptake.

Management Techniques

Sowing time and density

In Mediterranean climates, autumn-sown lupin crops often give the best yields (Annicchiarico and Carroni, 2009). Farther north, autumn sowing is not feasible due to the longer and colder winters. Narrow-leaved lupin cultivars tend to have a higher frost tolerance than white lupin ($-8/-10^{\circ}\text{C}$ versus $-4/-6^{\circ}\text{C}$), so are more suitable for early spring sowing. However, if the weather stays cold, growth is slow and weeds become a problem. Therefore organic lupin growers in the Netherlands tend to sow their crops no earlier than late March or early April (Prins, 2014).

Optimum plant density is cultivar-dependent. In branching cultivars, increasing plant density will generally decrease the level of branching and reduce the number of pods per plant, but ripening will be earlier and more uniform, with less variation in seed number per pod and mean seed weight (Herbert, 1977, 1978). However, dense crops tend to be more susceptible to fungal diseases such as *Sclerotinia* and *Botrytis*.

Fertilization

No significant positive yield responses to nitrogen (N) fertilization were observed in field trials in northern Europe (Prins, 2014). In Dutch field experiments, fertilization with potassium sulfate did not increase yields, but significantly reduced alkaloid levels, thus improving quality. This effect was greater in cultivars with intrinsically high alkaloid levels, and more pronounced in crops grown on soils low in potassium (Prins, 2014; Prins and Nuijten, 2015).

Nodulation

Good nodulation is essential for lupin production and inoculation with *Bradyrhizobium* is nearly always recommended, although lupin has been grown successfully on sandy soils without inoculation or history of lupin cultivation. Inoculation

is not considered necessary where lupin or serradella (*Ornithopus sativus* Brot.) has recently been grown successfully, and seems to be more important in soils with less favourable conditions (e.g. pH > 6.5).

Weed control

Weeds compete effectively against lupins. Sufficient plant density helps to reduce weed growth in these crops (Herbert *et al.*, 1978; Isaac *et al.*, 2000), but chemical or mechanical weed control remains necessary. Harrowing four to five times in the first 2 months after sowing has been shown to effectively reduce weed populations to acceptable levels, without damaging the lupin crop (Jensen *et al.*, 2004c). Options for chemical weed control are limited as lupin is susceptible to most post-emergence chemicals. Therefore, weed control often combines pre-emergence herbicides with post-emergence harrowing (Prins, 2015).

Irrigation

The response of lupin to irrigation has been studied in various experiments. In general, irrigation is found to increase seed yield, as long as irrigation levels do not exceed crop water requirements (Herbert and Hill, 1978; Kang *et al.*, 2008, Hill *et al.*, 2011). Nevertheless, irrigation has also been found to increase infestation of lupin by grey mould (*Botrytis cinerea* Pers.), leading to yield losses (Jensen *et al.*, 2004b).

Yields and cultivars

There is little commercial breeding of lupin in Europe. Breeding of narrow-leaved lupin is concentrated in the northern parts of Europe with Saatzucht Steinach in Germany, two breeding companies in Poland (Hodowla Roślin Smolice and Poznańska Hodowla Roślin) and two individual lupin breeders in Denmark, distributing through DLF Trifolium. In Germany, cultivars such as 'Boregine', 'Haagena' and 'Sonate' gave the highest yields in variety trials in 2009–2011 on fine-textured, deep loess soils, with yields of 3.5–5 t/ha (Guddat *et al.*, 2011). The yields of the same lupin cultivars on coarser textured, sandy soils was significantly lower (2.0–3.5 t/ha) and more variable (Guddat *et al.*, 2011). This is supported by field trials on sandy and light-clayey soils, in spring–summer crop cycle, in the Netherlands in 2008 and 2009, where average yields on light-clayey soils exceeded the yield on sandy soils by 16% in 2008 and 67% in 2009 (Prins and Nuijten, 2015). Different cultivars have been developed for different purposes, for example: (i) cultivars with very low alkaloid levels, suitable for human consumption ('Borlu' and 'Vitabor'); (ii) cultivars with very high protein contents ('Probor'); and (iii) cultivars that exhibit early ripening ('Haags Blaue' and 'Boruta'). In Germany the early ripening, non-branching cultivars

are out-yielded on most soil types by the branching cultivars. Further north, in Denmark, early ripening is considered more important as the growing season is restricted, so early ripening is necessary for certainty of harvest. For this reason, breeding has been focused on developing early ripening, branching ('Iris') and non-branching cultivars ('Prima', 'Viol' and 'Primadonna'). In Finland, a breeding programme has targeted non-branching narrow-leaved lupins with an even shorter growing period (85–115 days) to make them suitable for the short Finnish growing season (Kurlovich *et al.*, 2011). In Germany, a lot of attention was given to resistance to *Fusarium* wilt. In the maritime climate regions of Western Europe, *Sclerotinia* and *Botrytis* play a much larger role than in the continental climate regions of eastern Germany and Poland. Hence the Danish cultivar 'Iris' showed much more stable yields than the most productive German cultivars 'Boregine', 'Haagena' and 'Sonate' and Polish cultivars 'Bojar', 'Dalbor' and 'Regent' in variety trials in 2007–2009 and 2011–2013. The yields of the best-performing narrow-leaved lupin cultivars coincides with the yields found in Germany: 3.4–4.8 t/ha on low-calcareous clay soils and 2.5–4.5 t/ha on sandy soils (Prins, 2015; Prins and Nuijten, 2015).

For yellow lupin, breeding is limited to Poland, as breeding activities in other countries (Germany and Denmark) were terminated largely due to the low yield expectations and disease susceptibility (anthracnose). In variety trials in the Netherlands, yellow lupin produced 1.5–2.5 t/ha on sandy soils where the best narrow-leaved lupins produced 1–2 t/ha more.

Breeding activity on white lupin in northern Europe has also declined. Germany had its own white lupin cultivar ('Feodora') bred by Saaten Union, but it is no longer available in Germany and is maintained only in France. Recently, a small Dutch breeder (Globe Seeds) started breeding *L. albus*, but no commercial cultivars are available yet. In the Netherlands, a small breeding programme has been started at the Louis Bolk Institute, looking for calcium-tolerant lupins suitable for young sea-clay soils, using breeding lines from both Globe Seeds and a Danish/Egyptian breeding programme with calcium-tolerant Egyptian germplasm (Nuijten and Prins, 2013). The main breeding activity in white lupin, however, is in France (INRA and, later on, Jouffray-Drillaud), whereas a public breeding programme exists in northern Italy. While breeding of white lupin in northern Europe is focused on spring-sown cultivars, breeding in France and Italy is focused on autumn-sown materials. The French cultivars from INRA have been tested in the UK (at Rothamsted) and showed very good production potential (3–5 t/ha) (Milford and Shield, 1996), although extra focus has been given to earliness of maturity and non-branching character. The non-branching cultivar 'Lucyanne' performed well, although it showed very little tolerance to calcareous soils (Kerley *et al.*, 2004). The French cultivars 'Ludet', 'Luxe' and 'Lucille' have been tested in central (Mediterranean climate) and northern (sub-continental climate) parts of Italy and compared to a local cultivar ('Multitalia') and a land-race from the Molise region. In both locations, the Italian cultivars out-performed the French, yielding up to 5 t/ha when sown during the optimum sowing period (Annicchiarico and Carroni, 2009). Other trials in southern Italy reported lower yield for white (2.2 t/ha) yellow (0.8–1.6 t/ha) and narrow-leaved lupin (0.5 t/ha) (Gresta *et al.*, 2010).

Crop Rotation

Improved yields in the following crop

In field trials in the Netherlands, residual N levels in the soil (0–90 cm) directly after harvest were 40–60 kg/ha, 15–25 kg/ha more than those after the cultivation of spring wheat or barley fertilized with 100 kg/ha of mineral N fertilizer. Crop residues (straw, pods, leaves and roots) leave an extra 40–50 kg/ha of N to be mineralized for the next crop (Prins, 2014).

In field trials in Denmark, unfertilized winter barley grown after lupins showed a 3-year average yield increase of 1.31 t/ha or 77% on sandy soils and 0.87 t/ha or 36% on loamy soils compared with that after oat (1.69 t/ha on sandy soils and 2.42 t/ha on loamy soils). With increased N fertilization of the winter barley crop (120 kg/ha) on sandy soils, the pre-crop advantage of lupin over oat declined to 0.76 t/ha (15% yield increase). A yield increase at such high N-fertilization rates indicates that probably more than just N transfer from the lupin to the barley was responsible for the pre-crop benefit, and phosphorus (P) mobilization or improved soil structure could be involved. On loamy soils, the yield increase in the winter barley after lupin instead of oat was observed up to a N-fertilization rate of 90 kg/ha. In 2 of the 3 years, winter barley yield with 120 kg/ha of fertilizer N after lupin decreased, whereas that after oat increased, probably due to the higher susceptibility of over-fertilized barley to diseases and lodging. Through the entire study, the effect of lupin on the yield of winter barley at different N levels was similar to that of pea, including the decrease in yield on loamy soils at higher N fertilization levels (Jensen *et al.*, 2004b). The observed yield increases of cereals after lupin and pea in this study is confirmed by other studies in Germany with cereals grown after faba bean or pea, where yield increases of 71% were observed at low N fertilization rates, but even at high fertilization rates a yield increase of 10–30% was still found (Entrup *et al.*, 2003).

Diseases and Pests

Soil-borne diseases

If lupins are grown too frequently in a crop rotation, soil-borne diseases can build up and cause substantial yield losses. Within the legumes, the most important soil-borne pathogens are largely host-specific, with lupins mainly affected by *Fusarium oxysporum* and *Fusarium solani* (Jensen *et al.*, 2004a). These effects should be taken into account in crop rotations.

Mammals and birds

The sweet domesticated lupin, with its reduced alkaloid levels, is an attractive food source for deer, rabbits and hares. Crop damage from these herbivores is mostly limited to field edges. Damaged lupin is able to form new shoots, reducing the

loss in yield. The forming of new shoots, however, delays the development and ripening of the crop, causing problems of uneven ripening. In contrast to pea, lupin crops are not very susceptible to bird damage.

Insects

Weevils and aphids form the main insect problems in lupin. Leaf weevils (*Sitona* spp.) not only damage the foliage but also the roots and nodules, affecting N fixation and causing severe yield losses (Kaufmann *et al.*, 2009). In areas where the frequency of legumes in crop rotations is high, weevil populations can be a serious problem for lupin production. In contrast, yield losses from aphids (e.g. lupin aphid, black bean aphid) are generally limited.

Fungal diseases

The agricultural lupins are susceptible to various fungal diseases, and fungi are often the principal cause of lupin yield losses. One of the main reasons why lupin breeding in northern Europe focuses on *L. angustifolius* is because of its relative resistance to anthracnose (*Colletotrichum lupini*), which causes great damage in *L. albus* and particularly in *L. luteus*. A second important fungal disease in lupin is caused by species of *Fusarium* (*F. oxysporum* and *F. solani*), which cause emergence problems, growth inhibition and late wilt. Disease pressure is particularly high in narrow crop rotations. The same is true for brown leaf spot (*Pleiochaeta set-tosa*), which has become a serious problem in narrow crop rotations in Australia (Kaufmann *et al.*, 2009). In wider rotations, brown leaf spot normally occurs as a ripening disease, causing only slight yield losses. Finally, in the moist oceanic climates of Western Europe, lupin production may also be affected by *Botrytis cinerea* and *Sclerotinia sclerotiorum*.

References

- Abberton, M.T. and Mizen, T. (2008) Improvement of yellow and narrow leaf lupins for the United Kingdom. In: Palta, J.A. and Berger, J.D. (eds) *Lupins for Health and Wealth, Proceedings of the 12th International Lupin Conference*, Fremantle, Western Australia, 14–18 September 2008. International Lupin Association, Canterbury, New Zealand, pp. 271–274.
- Adhikari, K.N., Buirchell, B.J., Thomas, G.J., Sweetingham, M.W. and Yang H. (2009) Identification of anthracnose resistance in *Lupinus albus* L. and its transfer from landraces to modern cultivars. *Crop and Pasture Science* 60, 472–479.
- Adhikari, K.N., Edwards, O.R., Wang, S., Ridsdill-Smith, T.J. and Buirchell, B. (2012) The role of alkaloids in conferring aphid resistance in yellow lupin (*Lupinus luteus* L.). *Crop and Pasture Science* 63, 444–451.
- Adhikari, K.N., Thomas, G.J., Diepeveen, D. and Trethowan, R. (2013) Overcoming the barriers of combining early flowering and anthracnose resistance in white lupin (*Lupinus albus* L.). *Crop and Pasture Science* 64, 914–921.

- Agizzio, A.P., Carvalho, A.O., Ribeiro, S. de F.F., Machado, O.L., Alves, E.W., Okorokov, L.A., Samaroo, S.S., Block, C. Jr, Prates, M.V. and Gomes, V.M. (2003) A 2S albumin-homologous protein from passion fruit seeds inhibits the fungal growth and acidification of the medium by *Fusarium oxysporum*. *Archives of Biochemistry and Biophysics* 416, 188–195.
- Annicchiarico, P. and Carroni, A.M. (2009) Diversity of white and narrow-leaved lupin genotype adaptive response across climatically-contrasting Italian environments and implications for selection. *Euphytica* 166, 71–81.
- Annicchiarico, P. and Thami-Alami, I. (2012) Enhancing white lupin (*Lupinus albus* L.) adaptation to calcareous soils through lime-tolerant plant germplasm and *Bradyrhizobium* strains. *Plant and Soil* 350, 134–144.
- Annicchiarico, P., Boschini, G., Manunza, P. and Arnoldi, A. (2014) Quality of *Lupinus albus* L. (white lupin) seed: extent of genotypic and environmental effects. *Journal of Agricultural and Food Chemistry* 62, 6539–6545.
- Blagrove, R.J. and Gillespie, J.M. (1975) Isolation, purification and characterisation of the seed globulins of *Lupinus albus*. *Australian Journal of Plant Physiology* 2, 1327.
- Boschini, G., D'Agostina, A., Annicchiarico, P. and Arnoldi, A. (2007) The fatty acid composition of the oil from *Lupinus albus* cv. Luxe as affected by environmental and agricultural factors. *European Food Research and Technology* 225, 769–776.
- Brand, J.D., Tang, C. and Graham, R.D. (2000) The effect of soil moisture on the tolerance of *Lupinus pilosus* genotypes to a calcareous soil. *Plant and Soil* 219, 263–271.
- Capraro, J., Magni, C., Fontanesi, M., Budelli, A. and Duranti, M. (2008) Application of two-dimensional electrophoresis to industrial process analysis of proteins in lupin-based pasta. *LWT Food Science and Technology* 41, 1011–1017.
- Chen, Y.L., Dunbabin, V.M., Diggle, A.J., Siddique, K.H.M. and Rengel, Z. (2012) Assessing variability in root traits of wild *Lupinus angustifolius* germplasm: basis for modelling root system structure. *Plant and Soil* 354, 141–155.
- Chiofalo, B., Lo Presti, V., Chiofalo, V. and Gresta, F. (2012) The productive traits, fatty acid profile and nutritional indices of three lupin (*Lupinus* spp.) species cultivated in a Mediterranean environment for the livestock. *Animal Feed Science and Technology* 171, 230–239.
- Christiansen, J.L., Sherow, R. and Ortiz, R. (1999) White lupin (*Lupinus albus* L.) germplasm collection and preliminary *in situ* diversity assessment in Egypt. *Genetic Resources and Crop Evolution* 46, 169–174.
- Coulombe, B.A., Chaney, R.L. and Wiebold, W.J. (1984) Bicarbonate directly induces iron chlorosis in susceptible soybean cultivars. *Soil Science Society of America Journal* 48, 1297–1301.
- Cowling, W.A. and Gladstones, J.S. (2000) Lupin breeding in Australia. In Knight, R. (ed.) *Linking Research and Marketing Opportunities for Pulses in the 21st Century. Current Plant Science and Biotechnology in Agriculture* 34. Kluwer Academic Publishers, Dordrecht, the Netherlands, pp. 541–547.
- Cowling, W.A., Huyghe, C., Swiecicki, W., Gladstones, J.S., Atkins, C.A. and Hamblin, J. (1998) Lupin breeding. In: Gladstones, J.S., Atkins, C.A. and Hamblin, J. (eds) *Lupins as Crop Plants: Biology, Production and Utilization*. Cambridge University Press, Cambridge, pp. 93–120.
- Croxford, A.E., Rogers, T., Caligari, P.D. and Wilkinson, M.J.U. (2008) High resolution melt analysis to identify and map sequence tagged site anchor points onto linkage maps: a white lupin (*Lupinus albus* L.) map as an exemplar. *New Phytologist* 180, 594–607.
- Dervas, G., Doxastakis, G., Hadjisavva-Zinoviadi, S. and Triantafillakos, N. (1999) Lupin flour addition to wheat flour doughs and effect on rheological properties. *Food Chemistry* 66, 67–73.
- Duranti, M., Restani, P., Poniatowska, M. and Cerletti, P. (1981) The seed globulins of *Lupinus albus*. *Phytochemistry* 20, 2071–2075.

- Duranti, M., Consonni, A., Magni, C., Sessa, F. and Scarafoni, A. (2008) The major proteins of lupin seed: characterization and molecular properties for use as functional and nutraceutical ingredients. *Trends in Food Science and Technology* 19, 624–633.
- Eastwood, R.J., Drummond, C.S., Schifino-Wittmann, M.T. and Hughes, C.E. (2008) Diversity and evolutionary history of lupins – insights from new phylogenies. In: Palta, J.A. and Berger, J.D. (eds) *Lupins for Health and Wealth, Proceedings 12th International Lupin Conference*, Fremantle, Australia, 14–18 September 2008. International Lupin Association, Canterbury, New Zealand, pp. 346–354.
- Egaña, J.I., Uauy, R., Cassorla, X., Barrera, G. and Yañez, E. (1992) Sweet lupin protein quality in young men. *Journal of Nutrition* 122, 2341–2347.
- Eickmeyer, F. (2008) Narrow leafed lupin breeding in Saatzucht Steinach a private company integrated in a network of research and development. In: Palta, J.A. and Berger, J.D. (eds) *Lupins for Health and Wealth, Proceedings of the 12th International Lupin Conference*, Fremantle, Western Australia, 14–18 September 2008. International Lupin Association, Canterbury, New Zealand, pp. 312–314.
- El-Adawy, T.A., Rahma, E.H., El-Bedawey, A.A. and Gafar, A.F. (2001) Nutritional potential and functional properties of sweet and bitter lupin seed protein isolates. *Food Chemistry* 74, 455–462.
- Entrup, N.L., Kivelitz, H. and Schlett, G. (2003) Untersuchungen zur Grünlandbewirtschaftung in nordrhein-westfälischen Betrieben – Pflanzenbestände, Erträge, Futterqualitäten, Nährstoffbilanzen. 5. DLG-Grünlandtagung 2003, die 10.000 kg-Herde auf dem Grünland. DLG e.V, Frankfurt am Main, Germany.
- European Commission (2006) European Commission Directive, 2006/142/EC. Available at: <http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2006:368:0110:0111:EN:PDF> (accessed 19 October 2016).
- FAOSTAT (2014) Statistics Database of the Food and Agriculture Organization of the United Nations. Food and Agriculture Organization of the United Nations, Rome. Available at: <http://faostat3.fao.org/home/E> (accessed 21 October 2014).
- Germplasm Resources Information Network (GRIN) (2013) GRIN National Genetic Resources Program. United States Department of Agriculture (USDA), Agricultural Research Service. Available at: www.ars-grin.gov. (accessed 1 August 2013).
- Gourinath, S., Alam, N., Srinivasan, A., Betzel, C. and Singh, T.P. (2000) Structure of the bifunctional inhibitor of trypsin and alpha-amylase from ragi seeds at 2.2 Å resolution. *Acta Crystallographica D Biological Crystallography* 56, 287–293.
- Gresta, F., Avola, G., Abbate, V., Magazzù, G. and Chiofalo, B. (2010) Lupin seed for crop-live-stock food chains. *Italian Journal of Agronomy* 4, 333–340.
- Guddat, Ch., Schreiber, E. and Farack, M. (2011) *Landessortenversuche in Thüringen – Lupinen (Variety Trials in Thüringen – Lupins)*. Thüringer Landesanstalt für Landwirtschaft, Jena, Germany.
- Hamblin, J., Barton, J., Sanders, M. and Higgins, T.J.V. (2005) Factors affecting the potential for gene flow from transgenic crops of *Lupinus angustifolius* L. in Western Australia. *Australian Journal of Agricultural Research* 56, 613–618.
- Herbert, S.J. (1977) Growth and yield of *Lupinus albus* at different plant populations. *New Zealand Journal of Agricultural Research* 20, 459–465.
- Herbert, S.J. (1978) III Seed yield relationships of *Lupinus angustifolius* cv. Unicrop. *New Zealand Journal of Agricultural Research* 21, 483–489.
- Herbert, S.J. and Hill, G.D. (1978) II. Components of seed yield of *Lupinus angustifolius* cv. WAU11B. *New Zealand Journal of Agricultural Research* 21, 475–481.
- Herbert, S.J., Lucas, R.J. and Pownall, D.B. (1978) Weed suppression in high density sowings of lupins. *New Zealand Journal of Experimental Agriculture* 6, 299–303.
- Hill, G.D., Kang, S. and McKenzie, B.A. (2011) Too much water is not a good thing. In: Naganowska, B., Kachlicki, P. and Wolko, B. (eds) *Lupin Crops – an Opportunity for Today, a Promise for the*

- Future, Proceedings of the 13th International Lupin Conference*, Poznan, Poland, 6–10 June 2011. International Lupin Association, Canterbury, New Zealand, pp. 133–135.
- Hughes, C. and Eastwood, R. (2006) Island radiation on a continental scale: exceptional rates of plant diversification after uplift of the Andes. *Proceedings of the National Academy of Sciences of the USA* 103, 10334–10339.
- Iqbal, M.J., Sujan, M., Ahsan, R., Kianian, S.F., Coyne, C.J., Hamama, A.A., Narina, S.S. and Bhardwaj, H.L. (2012) Population structure and linkage disequilibrium in *Lupinus albus* L. germplasm and its implication for association mapping. *Theoretical Applied Genetics* 125, 517–530.
- Isaac, W.A.P., Hill, G.D., McKenzie, B.A., Bourdôt G.W. and Frampton, C. (2000) Effect of crop morphology and density on crop and weed productivity. *Agronomy New Zealand* 30, 161–168.
- Jensen, B., Bødker, L., Larsen, J., Knudsen, J.Ch. and Jørnsgaard, B. (2004a) Specificity of soil-borne pathogens on grain legumes. Poster presented at the 5th European Conference on Grain Legumes, Dijon, France, 7–11 June 2004.
- Jensen, R.J., Joernsgaard, B., Andersen, M.N., Christiansen, J.L., Mogensen, V.O., Friis, P. and Petersen, C.T. (2004b) The effect of lupins as compared with peas and oats on the yield of the subsequent winter barley crop. *European Journal of Agronomy* 20, 405–418.
- Jensen, R.K., Rasmussen, J. and Melander, B. (2004c) Selectivity of weed harrowing in lupin. *Weed Research* 44, 245–253.
- Kang, S., McKenzie, B.A. and Hill, G.D. (2008) Effect of irrigation on growth and yield of *Kabuli* chickpea (*Cicer arietinum* L.) and narrow-leaved lupin (*Lupinus angustifolius* L.). *Agronomy New Zealand* 38, 11–32.
- Käss, E. and Wink, M. (1997a) Molecular phylogeny and phylogeography of the genus *Lupinus* (family Leguminosae) inferred from nucleotide sequences of the *RbcL* gene and ITS 1+2 sequences of rDNA. *Plant Systematics and Evolution* 208, 139–167.
- Käss, E. and Wink, M. (1997b) Phylogenetic relationships in the Papilionoideae (family Leguminosae) based on nucleotide sequences of cpDNA (*rbcl*) and ncDNA (ITS1 and 2). *Molecular Phylogenetics and Evolution* 8, 65–88.
- Kaufmann, K., Schachler, B., Thalmann, R. and Struck, C. (2009) *Pilzkrankheiten und Schädlinge bei Süßslupinenarten*. UFOP, Berlin, Germany, 39 pp.
- Kaufmann, K., Thalmann, R., Schachlerl, B., Saal, B. and Struck, C. (2011) Characterization of soil-borne root and stem rot diseases in narrow-leaved lupin cultivation in north-east Germany and development of screening methods for resistance breeding. In: Naganowska, B., Kachlicki, P. and Wolko, B. (eds) *Lupin Crops – an Opportunity for Today, a Promise for the Future, Proceedings of the 13th International Lupin Conference*, Poznan, Poland, 6–10 June 2011. International Lupin Association, Canterbury, New Zealand.
- Kerley, S.J., Shield, I. F., Scott, T. and Stevenson, H. (2004) Field-based nutritional response evaluation of the intolerant white lupin (*Lupinus albus*) cultivar Lucyanne to a lime-amended soil. *Journal of Agricultural Science* 142, 153–161.
- Kurlovich, B.S., Stoddard, F.L. and Laasonen, R. (2011) Breeding of narrow-leaved lupin (*Lupinus angustifolius* L.) for Northern European growing conditions. In: Naganowska, B., Kachlicki, P. and Wolko, B. (eds) *Lupin Crops – an Opportunity for Today, a Promise for the Future, Proceedings of the 13th International Lupin Conference*, Poznan, Poland, 6–10 June 2011. International Lupin Association, Canterbury, New Zealand, pp. 79–84.
- Li, H., Wylie, S.J. and Jones, M.G.K. (2000) Transgenic yellow lupin (*Lupinus luteus*). *Plant Cell Reports* 19, 634–637
- Lukashevich, M.I., Ageeva, P.A., Sviridenko, T.V., Potchutina, N.A.N.V. and MisnikovaIn, N.V. (2011) Results and perspectives of lupin breeding in Russia. In: Naganowska, B., Kachlicki, P. and Wolko, B. (eds) *Lupin Crops – an Opportunity for Today, a Promise for the Future*,

- Proceedings of the 13th International Lupin Conference*, Poznan, Poland, 6–10 June 2011. International Lupin Association, Canterbury, New Zealand, pp. 118–121.
- Magni, C., Sessa, F., Accardo, E., Vanoni, M., Morazzoni, P., Scarafoni, A. and Duranti M. (2004) Conglutin γ , a lupin seed protein, binds insulin *in vitro* and reduces plasma glucose levels of hyperglycemic rats. *The Journal of Nutrition and Biochemistry* 15, 646–650.
- Milford, G.F.J. and Shield, I.F. (1996) The potential of lupins for UK agriculture. *Journal of the Royal Agricultural Society of England* 157, 84–91.
- Molvig, L., Tabe, L.M., Eggum, B.O., Moore, A.E., Craig, S., Spencer, D. and Higgins, T.J.V. (1997) Enhanced methionine levels and increased nutritive value of seeds of transgenic lupins (*Lupinus angustifolius* L.) expressing a sunflower seed albumin gene. *Proceedings of the National Academy of Sciences USA* 94, 8393–8398.
- Moneret-Vautrin, D.A., Guerin, L., Kanny, G., Flabbe, J., Fremont, S. and Morisset, M. (1999) Cross-allergenicity of peanut and lupine: the risk of lupine allergy in patients allergic to peanuts. *Journal of Allergy and Clinical Immunology* 104, 883–888.
- Nelson, M.N., Phan, H.T.T., Ellwood, S.R., Moolhuijzen, P.M., Hane, J., Williams, A., O'Lone, C.E., Fosu-Nyarko, J., Scobie, M., Cakir, M., Jones, M.G.K., Bellagrd, M., Ksiarkiewicz, M., Wolko, B., Barker, S.J., Oliver, R.P. and Cowling, W.A. (2006) The first gene-based map of *Lupinus angustifolius* L. – location of domestication genes and conserved synteny with *Medicago truncatula*. *Theoretical and Applied Genetics* 113, 225–238.
- Nelson, M.N., Moolhuijzen, P.M., Boersma, J.G., Chudy, M., Lesniewska, K., Bellgard, M., Oliver, R.P., Swiecicki, W., Wolko, B. and Cowling, W.A. (2010) Aligning a new reference genetic map of *Lupinus angustifolius* with the genome sequence of the model legume, *Lotus japonicus*. *DNA Research* 17, 73–83.
- Nuijten, E. and Prins, U. (2013) *Lupineveredeling voor kalkrijke bodems: onderzoek naar perspectievolle lijnen (Lupin Breeding for Calcareous Soils: Research into Potentially Interesting Breeding Lines)*. Louis Bolk Institute, Driebergen, the Netherlands, 33 pp.
- Papineau, J. and Huyghe, C. (2004) *Le Lupin Doux Protéagineux*. Editions France Agricole, Paris.
- Parisot, L., Aparicio, C., Moneret-Vautrin, D.A. and Guerin, L. (2001) Allergy to lupine flour. *Allergy* 56, 918–919.
- Phan, H.T.T., Ellwood, S.R., Adhikari, K., Nelson, M.N. and Oliver, R.P. (2007) The first genetic and comparative map of white lupin (*Lupinus albus* L.): identification of QTL for anthracnose resistance and flowering time, and a locus for alkaloid content. *DNA Research* 14, 59–70.
- Pilvi, T.K., Jauhiainen, T., Cheng, Z.J., Mervaala, E.M., Vapaatalo, H. and Korpela, R. (2006) Lupin protein attenuates the development of hypertension and normalises the vascular function of NaCl-loaded Goto-Kakizaki rats. *Journal of Physiology and Pharmacology* 57, 167–176.
- Písarikova, B. and Zraly, Z. (2010) Dietary fibre content in lupine (*Lupinus albus* L.) and soya (*Glycine max* L.) seeds. *Acta Veterinaria Brno* 79, 211–216.
- Pollard, N.J., Stoddard, F.L., Popineau, Y., Wrigley, C.W. and MacRitchie, F. (2002) Lupin flours as additives: dough mixing, breadmaking, emulsifying and foaming. *Cereal Chemistry* 79, 662–669.
- Prins, U. (2014) *Samenvatting experimenten teeltoptimalisatie Lupine in de Veenkoloniën 2011–2013 (Summary of Field Experiments Crop Optimisation Lupins in the Dutch Peat District)*. Louis Bolk Institute, Driebergen, the Netherlands, 12 pp.
- Prins, U. (2015) *Lupine voor menselijke consumptie: Teelthandleiding (Lupins for Human Consumption: Cultivation Guide)*. Louis Bolk Institute, Driebergen, the Netherlands, 24 pp.
- Prins, U. and Nuijten, E. (2015) Optimizing lupin production for human consumption in the Netherlands. In: *Developing Lupin Crop into a Major and Sustainable Food and Feed Source, Proceedings of the XIV International Lupin Conference*, Milan, Italy, 21–26 June 2015. International Lupin Association, Canterbury, New Zealand, pp. 66–69.

- Raza, S., Abdel-Wahab, A., Jørnsgård, B. and Christiansen, J.L. (2001) Calcium tolerance and ion uptake of Egyptian lupin landraces on calcareous soils. *African Crop Science Journal* 9, 393–400.
- Scarafoni, A., Magni, C. and Duranti, M. (2007) Molecular nutraceuticals as a means to investigate the positive effects of legume seed proteins on human health. *Trends in Food Science and Technology* 18, 454–463.
- Scarafoni, A., Ronchi, A. and Duranti, M. (2010) γ -Conglutin, the *Lupinus albus* XEGIP-like protein, whose expression is elicited by chitosan, lacks of the typical inhibitory activity against GH12 endo-glucanases. *Phytochemistry* 71, 142–148.
- Singh, C.K., Robinson, P.H. and McNiven, M.A. (1995) Evaluation of raw and roasted lupin seeds as protein supplements for lactating cow. *Animal Feed Science and Technology* 52, 63–76.
- Sironi, E., Sessa, F. and Duranti, M. (2005) A simple procedure of lupin seed protein fractionation for selective food applications. *European Food Research and Technology* 221, 145–150.
- Sirtori, C.R., Lovati, M.R., Manzoni, C., Castiglioni, S., Duranti, M., Magni, C., Morandi, S., D'Agostina, A. and Arnoldi, A. (2004) Proteins of white lupin seed, a naturally isoflavone-poor legume, reduce cholesterolemia in rats and increase LDL receptor activity in HepG2 cells. *Journal of Nutrition* 134, 18–23.
- Sprent, J.I. and McKey, D. (1994) *Advances in Legume Systematics, Part 5: The Nitrogen Factor*. The Royal Botanical Gardens, Kew, London.
- Tang, C. and Thomson, B.D. (1996) Effects of solution pH and bicarbonate on the growth and nodulation of a range of grain legume species. *Plant and Soil* 186, 321–330.
- Terras, F.R.G., Goderis, I.J., Van Leuven, F., Vanderleyden, J., Cammue, B.P.A. and Broekaert, W.F. (1992) *In vitro* antifungal activity of a radish (*Raphanus sativus* L.) seed protein homologous to non-specific lipid transfer protein. *Plant Physiology* 100, 1055–1058.
- Terruzzi, I., Senesi, P., Magni, C., Montesano, A., Scarafoni, A., Luzi, L. and Duranti, M. (2011) Insulin-mimetic action of conglutin-gamma, a lupin seed protein, in mouse myoblasts. *Nutrition, Metabolism and Cardiovascular Diseases* 21, 197–205.
- Vicenti, A., Toteda, F., Di Turi, L., Cocca, C., Perrucci, M., Melodia, L. and Ragni, M. (2009) Use of sweet lupin (*Lupinus albus* L.var. *Multitalia*) in feeding for Podolian young bulls and influence on productive performances and meat quality traits. *Meat Science* 82, 247–251.
- Wäsche, A., Müller, K. and Knauf, U. (2001) New processing of lupin protein isolates and functional properties. *Die Nahrung* 45, 393–395.
- Westengen, O.T., Jeppson, S. and Guarino, L. (2013) Global *ex-situ* crop diversity conservation and the Svalbard Global Seed Vault: assessing the current status. *PLoS ONE* 8, e64146.
- White, C.L., Tabe, L.M., Dove, H., Hamblin, J., Young, P., Phillips, N., Taylor, R., Gulati, S., Ahes, J. and Higgins, T.J.V. (2001) Increased efficiency of wool growth and live weight gain in Merino sheep fed transgenic lupin seed containing sunflower seed albumin. *Journal of the Science of Food and Agriculture* 81, 147–154.
- Wijayanto, T., Barker, S.J., Wylie, S.J., Gilchrist, D.G. and Cowling, W.A. (2009) Significant reduction of fungal disease symptoms in transgenic lupin (*Lupinus angustifolius*) expressing the anti-apoptotic gene baculovirus gene *p35*. *Plant Biotechnology Journal* 7, 778–790.
- Wink, M. (1992) The role of quinolizidine alkaloids in plant insect interactions. In: Bernays, E.A. (ed.) *Insect-Plant Interactions (Vol. IV)*. CRC Press, Boca Raton, Florida, pp. 133–169.
- Wink, M. (1993) Quinolizidine alkaloids. In: Waterman, P. (ed.) *Methods in Plant Biochemistry (Vol.8)*. Academic Press, London, pp. 197–239.
- Yang, H., Lin, R., Renshaw, D., Li, C., Adhikari, K., Thomas, G., Buirchell, B., Sweetingham, M. and Yan, G. (2010) Development of sequence-specific PCR markers associated with a polygenic controlled trait for marker-assisted selection using a modified selective genotyping strategy: a case study on anthracnose disease resistance in white lupin (*Lupinus albus* L.). *Molecular Breeding* 25, 239–249.

- Yang, H., Tao, Y., Zheng, Z., Li, C., Sweetingham, M. and Howieson, J. (2012) Application of next-generation sequencing for rapid marker development in molecular plant breeding: a case study on anthracnose disease resistance in *Lupinus angustifolius* L. *BMC Genomics* 13, 318.
- Yang, H., Tao, Y., Zheng, Z., Shao, D., Li, Z., Sweetingham, M., Buirchell, B. and Li, C. (2013a) Rapid development of molecular markers by next-generation sequencing linked to a gene conferring phomopsis stem blight disease resistance for marker-assisted selection in lupin (*Lupinus angustifolius* L.) breeding. *Theoretical and Applied Genetics* 126, 511–522.
- Yang, H., Tao, Y., Zheng, Z., Zheng, Q., Zhou, G., Sweetingham, M., Howieson, J. and Li, C. (2013b) Draft genome sequence and a sequence-defined genetic linkage map of the legume crop species *Lupinus angustifolius* L. *PLoS ONE* 8, e64799.
- Yoshie-Stark, Y., Bez, J., Wada, Y. and Wäsche, A. (2004) Functional properties, lipoxygenase activity, and health aspects of *Lupinus albus* protein isolates. *Journal of Agricultural and Food Chemistry* 52, 7681–7689.
- Zhu, H., Choi, H.-K., Cook, D.R. and Shoemaker, R.C. (2005) Bridging model and crop legumes through comparative genomics. *Plant Physiology* 137, 1189–1196.
- Zohary, D., Hopf, M. and Weiss, E. (2012) *Domestication of Plants in the Old World*, 4th edn. Oxford University Press, Oxford, 264 pp.

7

Developing Soy Production in Central and Northern Europe

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Abstract

The soybean is an important ingredient of livestock feed in Europe and is also widely used in foods. Most soy used in Europe is imported (about 97% as beans and meal), mainly from South America and the USA. European soy production is currently concentrated in the south (Italy) and south-east (Balkan countries). Based on research conducted in Sweden and Germany, this chapter provides pointers to the development of the soy crop in central and northern Europe. It provides an overview of the history of the development of the crop in northern Europe, outlines relevant recent field research, and discusses aspects of good production practice. We focus on new production areas, generally north of traditional production areas. In recent years, interest in growing soybeans has spread east and north from Romania and Italy and parts of France to Austria, Germany, Hungary, Slovakia, the Czech Republic, Poland and even the BeNeLux countries, the Baltic and Scandinavian countries, with subsequently rising acreages. In order to succeed with soybean cropping in central and northern Europe, cultivars of the 00, 000 or 0000 maturity groups should be used. Grain yield in Scandinavia is about 2 t/ha. Crops in Germany and Austria produce about 2.5–3.5 t/ha. Knowledge about locally adapted cultivars and production technology is needed to support the development of the crop in new production regions. To ensure profitability of this new cropping, infrastructure for processing to feed and food has also to be developed.

The Biology of Soy

Soybean (*Glycine max* (L.) Merr.) is familiar mainly as imported soybean meal used to fill Europe's plant protein deficit. The soybean is an annual plant ranging in height from about 35 cm to 130 cm. The flowers are small, typically 3–8 mm, white or purple in colour, and initiated in the leaf axil on the stem, often from the fifth node and higher. The pods are slightly curved, about 4–6 cm long, covered

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with small brown or grey hairs. During maturation the pods turn brown and the plant drops its leaves. By harvest time, the stem remains with dry, firm pods.

Soy is a short-day plant, which means that the initiation of flowering is dependent on a minimum and lengthening night period. As the days grow shorter after the summer solstice, soybean enters its reproductive phase with the sensitivity to shorter days dependent on genetic factors. After flowering, the number of days to maturity depends on temperature. The heat required to bring soy to maturity is expressed either in crop heat units (CHU) or growing degree days. These two figures are temperature sums derived from two slightly different development models. The CHU method uses a linear relationship for night-time development (with a 4.4°C base temperature for night) combined with a non-linear relationship for day-time development using a base temperature of 10°C and an optimum of 30°C, above which the rate of development declines with further temperature increases. In German field research, the heat sums are calculated using the Canadian heat sum system (Brown and Bootsma, 1993) which is based on the daily maximum and minimum temperature during the life of the crop and calculates a mean of day- and night-time temperatures separately as follows:

$$\text{CHU} = (\text{CHU}_{\text{day}} + \text{CHU}_{\text{night}})/2$$

in which

$$\text{CHU}_{\text{day}} = 3.33(T_{\text{max}} - 10) - 0.084(T_{\text{max}} - 10)^2 \text{ and } \text{CHU}_{\text{night}} = 1.8(T_{\text{min}} - 4.4)$$

Soy cultivars are divided into 14 maturity groups from 0000 (earliest) to X (latest). The cultivars in the 000 and 0000 groups (triple and quadruple zero) are adapted to longer days found at higher latitudes.

About 4.5 million ha of soy were grown in Europe including Russia in 2014, yielding 9 million t which is an average yield of 2 t/ha. In the European Union (EU) about 0.6 million ha were grown yielding 1.85 million t which is an average yield of 3.2 t/ha (Table 7.1). Yields were high in central Europe in 2014 because of good weather conditions. It compares with an average of 2.9 t/ha in Brazil, 3.2 t/ha in the USA and 2.8 t/ha in Argentina, which are the main exporting countries (FAOSTAT, 2016). Based on data for 2005–2013 provided by FAOSTAT, Saatzucht Donau (2015) report that over years the relationship between soybean and grain maize yields in Austria remains relatively consistent at 27:100 on average, varying only between 26:100 and 29:100. This indicates that yield variability in well-adapted cultivars is not greater than in other crops. European efforts to reduce the European protein deficit could include increasing soy production in central and northern Europe (i.e. Europe north of the Alps), alongside other supply-side measures such as expanding faba bean production. The demand for genetically modified (GM)-free plant protein further increases the opportunities for European-grown soy.

Status of Soybean Cropping Development

The soy research community in northern Europe is small. Current research addresses issues such as cropping systems, suitable cultivars and the processing of

Table 7.1. Area and yield of soy in the 18 main production countries in Europe 2014. (From Copa Cogeca, 2015; FAOSTAT, 2016; and estimates from the German Soy Association.)

Country	Area (ha)	Yield (t/ha)	Production (t)
Ukraine	1,792,900	2.2	3,881,930
Russia	1,915,895	1.4	2,596,635
Italy	232,867	4.0	933,140
Serbia	154,249	3.5	545,898
France	75,800	3.0	227,262
Romania	79,275	2.6	202,892
Croatia	47,104	2.8	131,424
Austria	43,800	2.7	118,100
Hungary	42,980	2.7	115,600
Republic of Moldova	52,800	2.1	109,300
Slovakia	33,227	2.5	83,905
Germany ^a	10,000	2.4	24,000
Greece ^b	7,500	2.8	20,900
Poland ^b	14,100	1.3	18,300
Czech Republic	7,242	2.3	16,493
Bosnia and Herzegovina	4,186	2.2	9,020
Switzerland	1,496	2.6	3,882
Spain	800	3.4	2,700

^aEstimates from the German Soy Association based on data from several German Länder.

^bFrom Copa Cogeca (2015).

soybeans for food and feed. In Sweden, research is maintained at the Research Institutes of Sweden, Uppsala (RISE) and partners at the Scandinavian Seed AB. There are ongoing field trials at the Åland Experimental Station in the Åland Islands of Finland. Farmers in southern Finland have experimented with soybean cropping since 2011. The Estonian Crop Research Institute in Jõgeva is active in breeding, but the area is still limited to less than 100 ha. There is also research on soybean in the Lithuanian Research Centre for Agriculture and Forestry in Babtai and at Pure Horticultural Research Centre.

In Germany, the University of Hohenheim has worked on soy since the 1970s. Supported by a national project to extend soybean cultivation in Germany, FiBL Deutschland e.V., Forschungsinstitut für biologischen Landbau (Research Institute of Organic Agriculture) in Frankfurt am Main, together with the Deutscher Sojaförderring (German soy information ring) at LTZ Augustenberg, have intensified the existing long-term experiments in five German states by coordinating tests of more than 50 cultivars on 33 sites all over Germany during the years 2011–2013. Additional tests for cold tolerance have been carried out at Julius Kühn-Institut (JKI), Bundesforschungsinstitut für Kulturpflanzen (Federal Research Centre for Cultivated Plants) in the Rostock area. The University of Kassel and Hochschule Osnabrück have worked on cultivation systems for cooler regions and the Landessaatzuchtanstalt (State Plant Breeding Institute) of Baden-Württemberg started a breeding programme for 000-tofu-beans. Details of the German research activities are provided by the Deutscher Soja-Förderring (2015).

Since 2013 the production area evolved from 7500 to 10,000 ha in 2014 and 17,600 ha in 2015.

Institut National de la Recherche Agronomique (INRA) has conducted a significant amount of research in France. While work on inoculation continues, INRA research on breeding has ceased but Terres Inovia and two private breeders continue work on soybeans in France. The production area declined from 134,000 ha in 1989 to 26,000 ha in 2008 but has recovered to 43,000 ha in 2013, 74,700 ha in 2014 and 122,000 in 2015. Recent increases have occurred in northern France. Breeding started recently in the Netherlands and two cultivars were listed in 2013. The production area was 30 ha in 2013 and 110 ha in 2014. In Poland, breeding started in 1974 and some cultivars were listed in 1994 and 2002. The production area is growing rapidly and reached 17,900 ha in 2013 and 14,100 ha in 2014. In the Czech Republic, the area reached 6500 ha in 2013, and 7200 ha in 2014, while Slovakia cultivated about 29,000 ha in 2013 and 33,000 ha in 2014. In Austria and Hungary the cultivation area in 2013 was about 42,000 ha each and about 1000 ha more in 2014 (FAOSTAT, 2016).

The Russian Vavilov Institute in St Petersburg has a collection of about 7000 soybean accessions of which it is estimated that 1238 can be classified as very early and suitable for the non-chernozem zone of Russia. Unfortunately, budget constraints prevent the institute from doing any major development work on soy. In Belarus, breeding of 00 cultivars is conducted by the Soya-North Co. in Minsk, but the extent of these activities is unclear. A more substantial effort on breeding exists in Ukraine.

History of Soy Development in Europe

Although the soybean has been cultivated for thousands of years, the first record of it in Europe is as late as the 1700s. It was mentioned by Kaempfer (1712) who was a German scientist who had lived for some years in Japan. The plant was later cultivated mainly in botanic gardens and not used for food or feed. The first record of soy cultivation is from Linné relating to a garden in the Netherlands in 1737 (Shurtleff and Aoyagi, 2007). More than a century later, an Austrian agronomist, Friedrich Haberlandt, promoted the use of soy after having received some seeds from the Japanese and Chinese delegations at the Vienna world fair in 1873. He organized a large study on the viability of soybeans with 160 sites in 1877 in almost all German-speaking countries, including all parts of the Habsburg Empire. He published the results in *Die Sojabohne* (Haberlandt, 1878). After his sudden death later in 1878, work on soybeans in Austria was almost abandoned.

In 1908, a shortage of cotton seed vegetable oil resulted in imports of soybeans from Japan via the USA. The soy oil was popular and this triggered cropping in central Europe from where it later spread throughout Italy, France, Russia and Germany. In Germany, interest in soy grew after World War I and this was followed by efforts to boost German production in the 1930s and during World War II. Four soybean cultivars were listed in Germany and cultivation was mandatory in relevant regions at that time (Drews, 2004). After World War II, soybean breeding in Germany continued at a low level and some cultivars that were less sensitive to day length were identified. Breeding continued in western Germany at the

University of Giessen and in East Germany (GDR) at Gatersleben and Dornburg. Some of the cultivars from Dornburg were quite successful and were sold to Saatbau Linz in Austria after the re-unification of Germany in 1990. In Austria, Johann Vollmann has worked on specific questions of soybean breeding at BOKU in Vienna since 1990. Saatbau Linz started soybean selection at the Reichersberg station in 1990 but stopped it in 1995–96 after a significant reduction in production area from 54,000 ha in 1993 down to around 13,000 ha from 1995 onwards, following the accession of Austria to the EU in 1995. In 2000 Saatbau Linz cooperated with Probstdorfer Saatzucht to create a common breeding company named 'Saatzucht Donau'. Soybean breeding in Austria started again in 2006 at Reichersberg and has been intensified since 2011 (Saatzucht Donau, 2015). In Switzerland soybean breeding started 1981 at Changins station, now part of Agroscope, and has produced several cultivars of interest for central Europe (e.g. 'Gallec', 'Opaline', 'Amandine').

In the UK, pioneering work was done as early as 1913 by J.L. North, curator of the Royal Botanic Society of London, in adapting soybeans to English conditions. By 1923, using early cultivars introduced from various sources, North selected two or three strains that matured fully and gave good yields under English conditions. North eventually surmounted great difficulties and in 1933–34 was able to raise England's first successful crop of soybeans at the Fordson Estates. Good crops were then produced each year up to 1936. With some help from William Morse of the United States Department of Agriculture (USDA), North acclimatized four early-maturing cultivars that gave good yields.

In 1968 Ray Whisker began experimenting with growing soybeans (especially large-seeded vegetable-type soybeans) in his garden near London. He soon built up the largest British seed collection in private hands. In 1969 he began growing cultivar 'Fiskeby V' from Sweden with good results, and by the 1970s this vegetable-type soybean was available from Thompson & Morgan for gardeners. By 1975, Whisker had evaluated more than 200 cultivars from 18 countries (Shurtleff and Aoyagi, 2007). Modern British crop development started again in 1998 with 0000 cultivars in the early 2000s and reached about 3000 ha. This declined to 150 ha in 2013.

Sven Holmberg of company Algot Holmberg & Söner, Fiskeby, Norrköping in Sweden was a pioneer in the breeding of early maturing cultivars (Holmberg, 1947). He made crosses based on cultivars from Japan, Canada and China in the late 1940s and introduced a series of cultivars called 'Fiskeby I' to 'V'. The last cultivar, 'Fiskeby V', was introduced in Sweden in 1968 and is still considered as one of the earliest and highest yielding soybeans for northern European conditions and is still used in breeding, including in Canada. Unfortunately, the company archive is lost and we have only fragments of original data left from field testing and the breeding cultivars used.

The Canadian government started a breeding programme in the 1980s for conditions as far north as Québec and Manitoba. This research resulted in special-purpose cultivars for Asian food markets. From the late 1980s on, these cultivars were also quite successful in Austria, the Czech Republic and Germany where a producer of organic tofu organized the first inclusion of three Canadian soybean cultivars in the German National List in 2005 ('Alma Ata', 'Lotus' and 'Primus'). Canadian cultivars were the basis for the development of soy cultivation in Bavaria

(e.g. 'Merlin 000' and 'Gentleman 0000') as well as in the upper Rhine valley (e.g. 'Ohgata 00' and 'Primus 00'). Switzerland is another source of new cultivars with a breeding programme at Agroscope. Companies in France breed not only for the southern areas (0, I cultivars) but also for the central and northern parts of the country with 00 and 000 cultivars.

The development of soy in Europe therefore has the benefit of quite an active breeding community and trade infrastructure, considering the size of the crop and its early stage of development. Saatbau Linz and Probstdorfer Saatzucht with Saatzucht Donau, Saatzucht Gleisdorf and RWA in Austria, ZIA in the Czech Republic, Delley Samen und Pflanzen AG in Switzerland (promoting the cultivars of Agroscope ACW), Euralis and RAGT from France and Pflanzenzucht Oberlimpurg (PZO) from Germany are examples of seed companies providing suitable cultivars.

Future Potential for Soy in Central and Northern Europe

In the 1940s, Scandinavian breeders used cultivars from Japan and Manchuria to breed for day-length neutrality, contributing to the foundation of northern European soy production. Today, the majority of cultivars on the market worldwide are too sensitive to day length and do not flower in northern Europe. The use of the maturity groups gives a general idea of the suitability of cultivars for a region. From our practical experience, we regard central and northern Europe as two potential production regions within each of which the combined response to day length and temperature are similar.

1. North of the Alps and the French Loire river and south of a line from Amsterdam to Berlin and Warsaw, including the northern half of France, southern BeNeLux countries, Switzerland and Austria (north of the Alps); southern and central Germany; the Czech Republic, Slovakia and southern Poland.
2. Further north to the North Sea and Baltic Sea: northern Netherlands, north of the Amsterdam–Berlin–Warsaw line, including the Baltic countries, Finnish Åland Islands, southern Sweden with Gotland, and Denmark.

Cultivars identified as 00 may perform well in a 000 region. Likewise, some 000 cultivars have been shown not to be suitable for Scandinavian conditions. Thus, regional field testing is required.

Suitability of cultivars

Advances in plant breeding are crucial to adapting soy for European conditions. In agreement with Canadian research, Mechtler and Hendl (2010) report the results of cultivar trials in Austria showing that breeding resulted in 1.6% and 1.2% yield increase per year for 000 and 00 cultivars, respectively, registered between 1990 and 2010. The yield potential increased from 2.8 t/ha to 3.9 t/ha for the 000 group and from 3.0 t/ha to 4.2 t/ha for the 00 group. Protein yield increased with grain yield and the individual seed weight also increased.

Table 7.2 shows that in any one region there may be a choice of suitable cultivars from across Europe, for example those bred in Austria and Switzerland can be high yielding in Sweden. This means that provided day-length neutrality and earliness of maturity requirements are met, cultivars selected in one region may be suited over a larger area. Therefore, the classification of cultivars according to maturity groups is only a guide. The descriptive list of cultivars from Austria (Ages, 2016) proposes a points scheme to give a finer maturity differentiation between cultivars with 1 for 0000 cultivars, points 2–4 for 000 cultivars, points 5–7 for 00 cultivars and 8 for 0 cultivars.

Site effects

Despite the wide adaptation of soy, there may be substantial site effects within regions, which means that local cultivar testing is particularly important

Table 7.2. Grain yield (at 14% moisture content) of early maturing soybean cultivars evaluated in the St Petersburg region 2003–2008 (adapted from Vishnyakova and Seferova, 2013) and of cultivars tested in southern Sweden in 2012 (adapted from Fogelberg, 2013).

St Petersburg region			Southern Sweden ^a		
Cultivar	Origin or grown in	Yield (t/ha)	Cultivar	Origin or grown in	Yield (t/ha)
'Fiskeby 1040-4-2'	Sweden	2.7	'Annushka'	Ukraine	1.3
'Mageva'	Russia, Ryazan	2.5	'Moravians'	Canada/Czech Republic	1.4
'Fiskeby 840-7-3'	Sweden	2.5	'Bohemians'	Canada /Czech Republic	1.5
'PEP 28'	Russia, St Petersburg	2.3	'Silesia'	Canada /Czech Republic	1.4
'Svetlaya'	Russia, Ryazan	2.3	'Brunensis'	Canada /Czech Republic	1.7
'PEP 27'	Russia, St Petersburg	2.2	'Sultana'	France/Germany	1.6
'SibNIIK 15/83'	Russia, Novosibirsk	2.1	'Klaxon'	France	1.7
'Altom'	Russia, Altay	1.8	'Merlin'	Canada/Austria, Germany	2.0
'Stepnaya 85'	Russia, Kemrovo	1.8	'Lissabon'	Canada/Austria, Germany	1.7
'KG 20'	Canada	1.6	'Capnor'	France/Austria	1.5
'SOER 4'	Russia, Saratov	1.4	'Gallec'	Switzerland/Austria	2.0
'USHI 6'	Russia, Ulyanovsk	1.3	'Paradis'	Switzerland	1.8

^aThe 2012 season in Sweden was characterized by low temperatures and high rainfall.

for the development of the crop. [Table 7.3](#) provides grain and protein yield data (mean of 3 years) for a range of well-adapted cultivars at three sites in Germany. Depending on site quality and cultivar, yields in Germany vary between 2.5 t/ha and 4.8 t/ha, protein contents vary from 37% to 43% and protein yields from 0.9 t/ha to 1.7 t/ha. Harvesting dates are influenced not only by the heat sums but also by weather conditions after physiological maturity of the crop.

Swedish field experiments have shown that yields of early cultivars can reach about 2.5 t/ha in that country. However, a cool and wet spring in combination with low summer temperatures may lower the yields considerably. In 2012, 14 cultivars were tested in southern Sweden. Those that earlier had proven to give high yield, such as the Czech (Canadian) cultivar 'Silesia', were low yielding due to the unusual cold and rainy summer while Austrian (Canadian) and Swiss cultivars such as 'Merlin' and 'Gallec' were still able to give acceptable yields ([Table 7.2](#)). Similar results were obtained in northern Germany (Rostock and Wolfsburg) and in northern Bavaria (Schweinfurt) while 'Merlin' and 'Gallec' yielded 3 t/ha and 3.3 t/ha, respectively, on a fertile loess near Kassel in central Germany. The results show that water supply during generative development as determined by soil texture is an important factor determining yield.

Table 7.3. Yield (at 14% moisture content) and protein yield, lodging and date of maturity of early matured soybean cultivars evaluated at three sites in Germany in 2011, 2012 and 2013. The average heat sums (crop heat units, CHU) accumulated by the crop and the annual rainfall (mm) as well as the Müncheberg soil quality rating (SQR)^a are provided for each site.

Cultivar	Beetzendorf (Altmark, Wolfsburg (2717°CHU, 575 mm precipitation, SQR 45) (northern Germany)		Salbitz (Dresden-Leipzig) (2965°CHU, 600 mm precipitation, SQR 86) (eastern Germany)		Cologne-Auweiler (2941°CHU, 750 mm precipitation, SQR 75) (western Germany)	
	Yield (t/ha)	Protein yield (t/ha)	Yield (t/ha)	Protein yield (t/ha)	Yield (t/ha)	Protein yield (t/ha)
'Lissabon'	3.11	1.07	3.90	1.29	3.51	1.18
'Merlin'	2.94	1.04	4.14	1.38	3.30	1.13
'Cordoba'	2.83	0.97	4.09	1.30	3.62	1.20
'Alma Ata'	2.82	1.02	4.00	1.33	–	–
'Sultana'	2.82	1.06	3.90	1.33	3.38	1.22
'Aligator'	2.76	0.97	4.19	1.39	3.40	1.14
'ES Mentor'	–	–	4.76	1.71	3.89	1.38
Mean	2.88	1.02	4.14	1.71	3.52	1.21
Maturity	11–23 September		21–27 September		26 September–16 October	
Lodging	2.3–4.3 (medium)		1.0–1.4 (low)		1.2–3.3 (low–medium)	

^aThe SQR system rates soil on a scale of 0–100 according to crop yield potential, whereby generally a high rating (i.e. nearer to 100) indicates soils that are water-retentive due to a favourable fine soil texture.

Identifying Potential – an Example from Germany

These results show that there is potential in northern Europe, but much more detailed local studies are required to identify more precisely where soy has the potential to compete economically within farming systems. To achieve this, a German government-funded research project (Wilbois *et al.*, 2014) examined the performance of up to 48 soy cultivars in 99 field experiments conducted at 38 sites across Germany.

While weather varied between seasons, the ranking of the sites in terms of heat sums remained relatively constant over the years. The average CHU heat sum for May–September 2005–2013 at the ‘warm’ sites was 3182. The corresponding heat sums for the medium and cool sites were 2914 and 2740, respectively. Here we present an analysis of the likelihood of a yield level being reached for sites characterized on the basis of heat sum, based on an evaluation of yields of 99 soybean cultivar experiments on 33 sites in Fig. 7.1. Figure 7.2 presents the distribution of trial yields for the sites characterized as warm, temperate and cool using heat sums. In the warm region, 75% of the crops yielded in excess of 2.5 t/ha while the corresponding number for the cool region (average heat sum 2740) was just over 50%. The temperate region with an average heat sum of 2914 was also

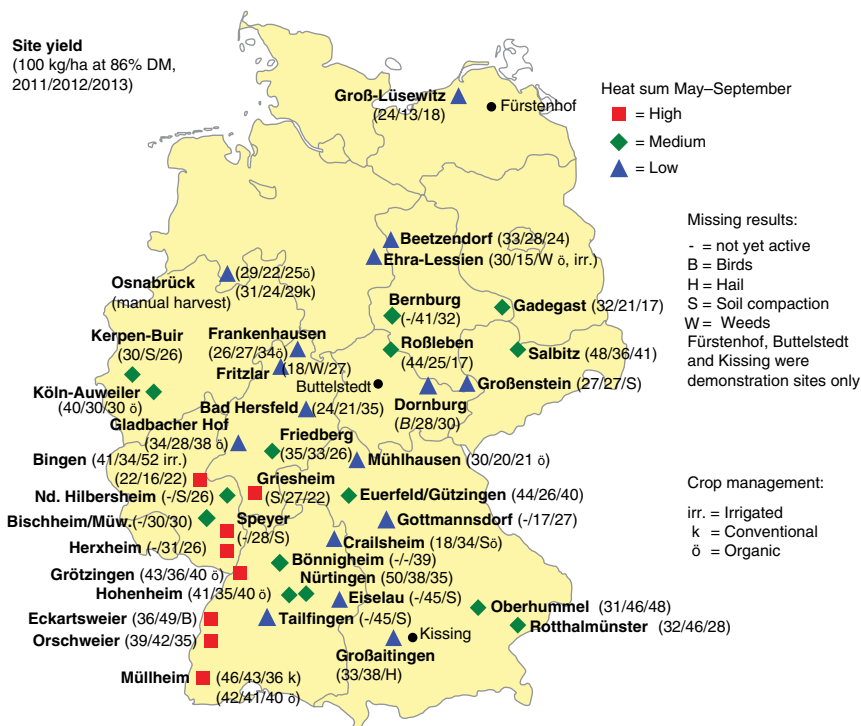


Fig. 7.1. The German field trial sites classified according to heat sum accumulation. The average yields for each site and year are shown (in units of 100 kg/ha). DM, Dry matter. (From Wilbois *et al.*, 2014.)

productive indicating that relatively small changes in heat sums between 2700 and 2900 have a significant effect on the likelihood of crop success.

These results support those of Hahn and Miedaner (2013) that show the effect of heat sums on yield level with indications of cultivar × environment interactions linked to the 00 and 000 classification (Fig. 7.3). In warmer regions the best yield is obtained by 00 cultivars (e.g. ‘ES Mentor’ in Region 1 with more than 3.5 t/ha) while in cooler regions 000 cultivars (e.g. ‘Merlin’ in Region 3) gave the highest yields but the overall yield level was lower.

From Wilbois *et al.* (2014) we can see that yields in German field trials may commonly vary from 2 t/ha or less in the north to 5 t/ha in the south, depending

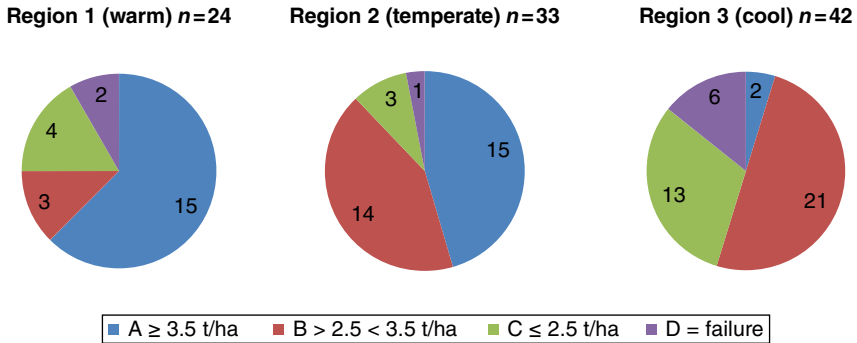


Fig. 7.2. Number of results (site mean) within three yield categories (3.5 t/ha or more, 2.5–3.5 t/ha, and less than 2.5 t/ha, plus failed crops for three regions as characterized by the heat sums into warm, medium (temperate) and cool. (From Wilbois *et al.*, 2014.)

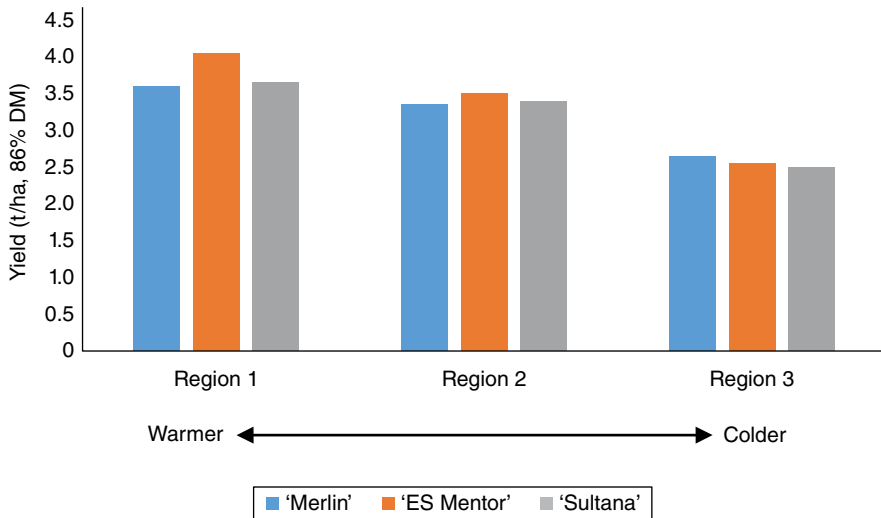


Fig. 7.3. Yields (grain at 14% moisture) of three soybean cultivars depending on regional heat sum. DM, Dry matter. (From Hahn and Miedaner, 2013.)

on heat sums and water supply in the summer. Our experience is that corresponding farm averages tend to vary from less than 2 t/ha to more than 3.5 t/ha, depending in particular on weather and soil conditions and weed management. Average yields in contract cultivation for organic tofu production in southern Germany have ranged from 2.1 t/ha to 2.8 t/ha in the last 10 years.

From a central European perspective, soybean yields in Scandinavia may seem to be low (see Table 7.2) but the protein yields are comparable to those of pea and faba bean, the amino acid profile is better, and there is the added benefit of the oil. There is, of course, also an increased risk of yield variations at these high latitudes due to climatic conditions. Soy is responding to development and yields are likely to increase by the use of improved cultivars and improved cropping systems in general.

Production Techniques

Soybean can be grown on a wide range of soils provided root development is not impeded by compaction. Optimum pH is about 6.5–7.0. Like other arable crops, soy performs well on water-retentive soils, so heavy soils are suitable if they warm up early in spring. Soils with a high mineral nitrogen supply, for example due to manure applications, are not suitable because of the suppression of nodulation and the risk of excessive vegetative growth.

Machinery used for cereals, oilseed rape and other legumes is also used for soy. Direct drilling can be used to reduce compaction by avoiding travel over prepared seedbeds. With conventional tillage, light seed drills followed by a light rolling are preferred under Scandinavian conditions to prevent compaction. Seed densities vary from 70–75 seeds/m² for 0000, 60–65 seeds/m² for 000 and 55–60 seeds/m² for 00 cultivars. In organic cultivation seed densities tend to be higher in order to compensate possible losses by intensive mechanical weeding. Row distances may vary from 12.5 cm (commonly used for cereals) to 75 cm (as is used for maize). Row distances in excess of 25 cm allow mechanical weed control and may be beneficial in northern Europe due to a better light penetration in the stand. Closer row spacing often gives taller unbranched plants, while rows 50–75 cm apart give bushy plants with 00 cultivars. Rows wider than 50 cm are not suitable for 000 and 0000 cultivars because of restricted branching. Emergence in difficult situations may be favoured by wider row distances (30–45 cm) due to the higher density in the rows. Precision seeding is also an option.

Inoculation with *Bradyrhizobium japonicum* is essential for optimum nitrogen fixation in soy. Some seed producers offer seeds that are inoculated and ready to sow. Where the farmer inoculates the seed, this must be done within 48 h of sowing, depending on the inoculum formulation. The process is quite easy, after a light soaking of the seeds, a fine-milled peat substrate containing the inoculum is added to them, thoroughly mixed and the seed is sown as normal. The inoculation of soy grown for the first time is twice that of subsequent crops. Pre-inoculated seeds should be additionally inoculated with the normal dose of fresh inoculum when sown on a field where soybean has never been grown. Even if rhizobia may

survive in some soils for up to 10 years, inoculation is cost-effective also in further cultivations on a given field, because it provides yield and protein-content benefits.

The soy plant is sensitive to weed competition in its early development, especially if cold and wet weather prevails. Weed control can be achieved using herbicides or mechanical methods. No herbicides are approved for control of annual or perennial weeds in soy in the Nordic countries, but there are initiatives to extend the range of approved herbicides. In other European countries, a few herbicides for soybean are approved, but some weeds such as *Convolvulus* or bindweed, thistle and *Solanum nigrum* are not well controlled with them and land infested with these should not be used. One or two herbicide treatments are sufficient in most cases, including combinations of pre- and post-emergence treatments. Pendimethaline may adversely affect soybean where soils get waterlogged. Some cultivars are also sensitive to metribuzine (e.g. 'ES Mentor', 'ES Senator', 'Mavka') if soil splashes on the leaves due to intensive rainfall.

In organic farming, inter-row weed control should be carried out as soon as the rows are visible. The use of a stale seedbed (i.e. preparing a seedbed well in advance of sowing and destroying weed seedlings before sowing) will control weeds until inter-row cultivation is possible. A tined weeder may also be used within a week after sowing and before crop emergence. If successful, mechanical weed control may result in higher yields and earlier maturity because selective herbicides have side effects on the crop.

Until now, there have been few problems with fungal diseases in northern Europe. Some problems with insects affecting the plant at early growth stages due to slow emergence have been reported by farmers. In very warm years, Vanessa caterpillars may affect soybeans north of the Alps. An increase in cropping area might increase the need for pest control. Experience in regions where soy has been grown for several decades (e.g. in Austria) indicates that the risk of a build-up of problems as production expands is low.

At the more northerly end of the production zone, diseases may strike during emergence if there is prolonged cold and wet weather. Soy is susceptible to sclerotinia, especially if grown in rotations with rapeseed and sunflower. *Diaporthe/Phomopsis* may be a problem under wet conditions, especially for seed production (Hahn and Miedaner, 2013).

Harvest and Processing of Soybean for Food or Feed

In Scandinavia, soy matures in late September and is usually ready for harvest in early October. Further south, soy usually ripens during September and harvesting in September enables the sowing of a winter cereal as a succeeding crop. Grain moisture content can decrease rapidly at this time when the crop has lost its leaves. When the beans are loose in the pods, humidity may vary by 5% between the afternoon and night-time. Seeds with moisture contents over 18% are difficult to dry because of the size of the beans (they have to be dried in two steps). Nevertheless, after mid-October soybean should be harvested even if moisture exceeds 20%, because opportunities to harvest under dryer conditions are rare at this point.

The soy pod is relatively resistant to shatter with some differences between cultivars and is easy to harvest with standard combine harvesters. The first pod on each plant is often close to the soil surface which may result in field losses. Flexible headers are available making it possible to cut the plants 2–4 cm above the soil surface and thus reduce field losses significantly. Experienced drivers can reduce losses substantially also with conventional headers. Axial-flow combine harvesters are better for grain quality, breaking fewer seeds than the usual shaker-based machines.

If stored for 6 months or longer, drying should be used to bring moisture contents to 12% or lower. When used for food or seed, drying temperature in the grain should not exceed 40°C.

For cattle it is possible to use raw beans as feed, but for pigs and poultry, heat treatment is needed to remove antinutritional factors such as trypsin inhibitors. There are several technical options: roasting (or 'toasting') with direct or indirect heat or microwaves. Heat treatment may be combined with humidity and/or pressure. Technology from the USA, South Africa and Europe has opened up opportunities for small-scale on-farm processing. Roasting can, for instance, be done by machines from EST GmbH in Austria (EcoToast), Roastech in South Africa, and from the Dilts-Wetzel Manufacturing Co. in the USA.

These machines carry out dry roasting at about 100–400 kg/h and can easily be installed on farms. In roasting, a balance is set between the heat required to reduce inhibitors and avoidance of heat damage that reduces digestibility. Using a compact modular design, the EcoToast system from EST GmbH in Austria uses electricity and internal heat recovery to treat the soy in a hydro-thermal process so that the air is quite saturated with water at about 150°C, delivering a seed internal temperature of 100°C. The electricity usage is about 90 kWh/t. The Dilts-Wetzel machine also uses indirect heat to avoid exposing the seeds to high temperatures.

Cold pressing of the beans can be done with machines used for oilseed rape. It requires more energy than oilseed rape and wear on machines is high. About 50% of the oil content can be removed by cold pressing. Where a fat-free meal is required, pressing must be combined with solvent extraction. This is often too costly and technically demanding for small-scale producers. In organic agriculture, chemical solvents are not allowed. Account needs to be taken of the oil content in blending for feeding.

Soybean grown in northern Europe can be used for food purposes, resulting in high sensory and texture qualities. The quality for the food industry depends mainly on the cultivar, which might be set contractually by the buyer. There are different cultivars for drinks, tofu or natto. Soy intended for foods such as 'milk', tofu, ice cream and yoghurt, must fulfil quality requirements such as taste, processing quality criteria, texture and hygienic qualities.

Prospects for Soybean in Northern Europe

Crops of soy (Fig. 7.4) are becoming a common sight north of the Alps. We can expect that soybean cropping will become more common in central and northern



Fig. 7.4. A crop of soy growing in the Rhine valley, Germany. (Photo credit: Jürgen Recknagel.)

Europe. Agronomists in the Nordic and Baltic countries, including Germany and Poland, have in recent years identified soy as a ‘new’ crop that, under some conditions, can be cropped as far as 59°N. This understanding combined with premium markets for GM-free soybean opens opportunities for its production, especially for food purposes. We must emphasize that this outcome depends on science-based crop development to provide suitable cultivars.

Further south, particularly in southern Germany, France, Austria and the Balkans, soybean is of special interest in organic agriculture where it may resolve rotational problems with pea and faba bean by introducing another legume, increasing the overall yields and margins. There are local as well as state-sponsored initiatives to promote the growing of soy. One such initiative is the Danube Soya Association (www.donausoja.org), which is a partnership between public bodies, farmers, farm suppliers, processors and scientists aimed at growing soy in the Danube basin producing an alternative to imported soybean. It is supported by both EU member and non-member states in the Danube basin extending over a significant proportion of European territory where the crop can be grown well.

Recent information from the Danube Soya Association indicates that cultivation is expanding mainly in conventional agriculture, competing mainly with wheat, maize and oilseed rape for land. In warmer regions, maize may be the main competitor for land, if not restricted by corn rootworm regulations. In drier regions such as northern Bavaria, soybean competes mainly with rapeseed as well as several cereals. In regions with adequate rainfall, such as upper Austria,

soybean competes well with cereals. Reichmuth and Schönberger (2012) reported that soybean competes well with current crops due to its positive effect on the following crop, which is normally winter wheat. The online margin calculator of the Bavarian State Institute for Agriculture (LfL) gives a detailed view of the competitiveness of organic and conventionally produced soybeans compared to other crops for the different parts of Bavaria, based on statistical data of several years. Normally soybeans can compete easily with other grain legumes as well as with barley and oats. For practical growing decisions, the availability of a contract for production is often decisive for farmers. Since 2008, the price ratio between soybean and maize at about 2.5 supports expansion of soybean. In organic agriculture, soybean is often among the most competitive field crops as it does not need nitrogen input, its price is more than double that of conventional soybean and its yields are about the same when weeds are well controlled.

References

- Ages (2016) Österreichische Beschreibende Sortenliste Sojabohne. Available at: www.ages.at (accessed 2 March 2016).
- Brown, D.M. and Bootsma, A. (1993) Crop heat units for corn and other warm season crops in Ontario. Ontario Ministry of Agriculture and Food Factsheet. Available at: <https://www.sojafoerderring.de/wp-content/uploads/2014/02/Berechnung-CHU-Uni-Guelph-Ontario.pdf> (accessed 17 October 2016).
- Copa Cogeca (2015) EU 28 Oilseeds Area and Production Estimates for Harvest 2014 and Sowing Intentions for Harvest 2015. Available at <http://www.copa-cogeca.be/Crops.aspx> (accessed 22 September 2015).
- Deutscher Soja-Förderring (2015) Das Sojaportal für Deutschland. Available at: www.sojafoerderring.de/ (accessed 17 September 2015).
- Drews, J. (2004) Die 'Nazi-Bohne'. Anbau, Verwendung und Auswirkung der Sojabohne im Deutschen Reich und Südosteuropa (1933–1945). Dissertation, Universität Münster, LIT Verlag, Münster, Germany, ISBN 978-3-8258-7513-8.
- FAOSTAT (2016) Statistics Database of the Food and Agriculture Organization of the United Nations, Rome. Available at: <http://faostat3.fao.org/home/E> (accessed 2 March 2016).
- Fogelberg, F. (2013) Soya beans and lupins 2012 – some results and conclusions of field experiments conducted for Scandinavian Seed AB. PowerPoint presentation at the Swedish Institute of Agricultural and Environmental Engineering (JT1), Uppsala, Sweden.
- Haberlandt, F. (1878) Die Sojabohne, Ergebnisse der Studien und Versuche über die Anbauwürdigkeit dieser neu einzuführenden Kulturpflanze. Verlag von Carl Gerold's Sohn, Vienna, Austria.
- Hahn, V. and Miedaner, T. (2013) Sojaanbau in der EU. DLG-Verlag, Frankfurt, Germany.
- Holmberg, S. (1947) Sojaförädling vid Fiskeby (Soya bean breeding at Fiskeby). *Försök och Forskning: under redaktion av jordbrukets upplysningsnämnd* 1, 8–10.
- Kaempfer, E. (1712) *Amoenitatum exoticarum politico-physico-mediciarum fasciculi V. Lemgoviae: Typis & Impensis Henrici Wilhelmi Meyeri, Aulae Lippiacae Typographi* 1712.
- Mechtler, K. and Hendler, M. (2010) Ertrags- und Qualitätsentwicklung bei Öl- und Eiweißfrüchten in der Sortenwertprüfung. Tagungsband der 61. Jahrestagung der Vereinigung der Pflanzenzüchter und Saatgutkaufleute Österreichs, 23–25 November 2010. Herausgeber Vereinigung der Pflanzenzüchter und Saatgutkaufleute Österreichs, pp. 79–86.
- Reichmuth, J. and Schönberger, H. (2012) Soja: Der Star von morgen? *Top agrar* 8, 70–74.

- Saatzucht Donau (2015) Zuchtprogramme in der Station Reichersberg: Sojabohne. Available at: www.saatzucht-donau.at/deutsch/ueberuns/ueberuns.htm (accessed 18 January 2015).
- Shurtleff, W. and Aoyagi, A. (2007) History of soy in Europe (incl. Eastern Europe and the USSR (1597–mid-1980s). In: *A Special Report on the History of Soybeans and Soyfoods around the World. History of Soybeans and Soyfoods: 1100 BC to the 1980s*. Soyinfo Center, Lafayette, California. Available at: www.soyinfocenter.com/HSS/europe1.php (accessed 17 September 2015).
- Vishnyakova, M. and Seferova, I. (2013) Soybean genetic resources for the production in the Non-Chernozem zone of the Russian Federation. *Legume Perspectives* 1, 7–9.
- Wilbois, K.-P., Spiegel, A.-K., Asam, L., Balko, C., Becker, H., Berset, E., Butz, A., Haase, T., Habekuß, A., Hahn, V., Heß, J., Horneburg, B., Hüsing, B., Kohlbrecher, M., Littmann, C., Messmer, M., Miersch, M., Mindermann, A., Nußbaumer, H., Ordon, F., Recknagel, J., Schulz, H., Spory, K., Trautz, D., Unsleber, J., Vergara, M., Vogel, R., Vogt-Kaute, W., Wedemeier-Kremer, B., Zimmer, S. and Zurheide, T. (2014) *Ausweitung des Sojaanbaus in Deutschland durch züchterische Anpassung sowie pflanzenbauliche und verarbeitungstechnische Optimierung. (Expansion of Soybean Cultivation in Germany through Adaptation by Breeding as well as Optimization of Crop Production and Processing Technology.)* Forschungsinstitut für biologischen Landbau (FiBL), Frankfurt am Main, Germany.

8

Legume-based Green Manure Crops

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Abstract

Legume-based green manures (LGMs) are crops that are grown with the specific purpose of improving soil quality and consequently the long-term productivity of crops. Although the traditional focus has been on the supply of nitrogen (N) to the system, they have a wide range of potential benefits that include improving soil quality, reducing soil erosion and increasing the biodiversity of farmland. LGMs are a key component of organic farming systems where the use of synthetic N fertilizers is not permitted. However, increases in the cost of inputs, concerns about environmental impacts of intensive use of agrochemicals, and the recently announced measures for the 'greening' of the European Common Agricultural Policy have led to renewed interest in the use of LGMs more widely. In Europe, the legumes in LGMs may be annual or perennial plants, grown on their own or more often as part of crop mixtures with a range of other crop types such as grasses or brassicas. The legumes most commonly grown are the clovers (*Trifolium* spp.), particularly red and white clover. Other legumes that may be grown to suit particular local goals or constraints include *Medicago* spp. (lucerne (alfalfa) and black medic), trefoils (*Lotus* spp.), vetches (*Vicia* spp.), lupins (*Lupinus* spp.), other minor forage legumes and grain legumes. To maximize fertility building in organic farming systems, LGMs are grown in place of cash crops for some of the crop rotation. In more intensive systems, LGMs may be grown for short periods between phases of regular crop production. This chapter reviews the use of LGMs in Europe and considers factors that affect N fixation in them and the transfer of fixed N to following crops. It examines how they can be integrated into practical rotational cropping systems and whether the economics of this makes the use of LGMs profitable. However, LGMs will not be agronomically or economically viable in all systems, and in these cases other types of green manures may be more appropriate. As demand for multifunctional agricultural systems grows, and is increasingly required by European agricultural policies, so does the potential for greater use of LGMs.

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Introduction

A green manure may be broadly defined as any crop that is grown with the specific purpose of improving the soil, and by implication the crops that are subsequently grown in it. They have a wide range of potential benefits that include reducing the loss of nutrients to the environment through leaching and surface runoff, improving soil structure and quality, reducing soil erosion, and increasing the biodiversity of farmland. Green manures improve soil quality by increasing organic matter content, enhancing structure and promoting more diverse and biologically active microbial communities, and they potentially reduce the use of plant protection products and fertilizers. They are annual or perennial plants, grown on their own or more often in crop mixtures, for a few months or up to several years between periods of regular crop production. In long-term orchard and vineyards they are grown between trees and vines.

Legume-based green manures (LGMs) are grown with the specific aim of increasing nitrogen (N) availability in a system by making use of the N fixed from the atmosphere by the legume. Overall, this process is the product of two processes: (i) N fixation while the LGM is growing; and (ii) transfer of any accumulated N to following crops once the LGM has been incorporated (ploughed in).

The use of green manures has a long history in agriculture. Reports relating to the 5th century BC refer to their benefits being as 'good as silk-worm excrement' for the soil in China. The ancient Greeks are recorded as incorporating faba beans (*Vicia faba* L.) into soil around 300 BC and Roman farmers were advised to sow their crops 'where grew the bean, the slender vetch, or the fragile stalks of the bitter lupine' (Pieters, 1927). The use of LGMs declined after World War II due to the increased use of fertilizers and herbicides. They continue to be a key component of organic farming systems, where the use of synthetic N fertilizers is not permitted. However, recent increases in the cost of inputs, concerns about environmental impacts of intensive use of agrochemicals, and the recently announced measures for the 'greening' of the European Common Agricultural Policy, have led to renewed interest in the use of LGMs more widely (Stobart and Morris, 2011).

This chapter reviews the use of LGMs in Europe and considers factors that affect N fixation in them and the transfer of fixed N to following crops. It examines how they can be integrated into practical rotational cropping systems and whether the economics of this makes the use of LGMs profitable.

Types of LGMs

Given that the primary aim is usually to fix atmospheric N, most LGMs are grown over the summer period when conditions for plant growth and N fixation are at their best. In all but the hottest areas of Europe this is over summer. Farmers have a wide choice of species to grow, coupled with flexible management options. The advantages of using a summer-grown LGM must be weighed against the disadvantage that they often replace a more profitable crop in the rotation.

In contrast, overwintering LGMs are either undersown into the main crop or sown in autumn, and incorporated into the soil the following spring, thus not taking the place of a cash crop. This is preferable to leaving the ground with no cover during the winter, but N fixation is often limited by the poor growing conditions at this time of year. In addition, the choice of species is restricted and weather windows for sowing and incorporation are usually narrow. Longer-term LGMs are usually established for 2 or 3 years as a part of an arable rotation (leys). On farms with livestock, the leys are usually grazed or cut for silage, whereas in a stockless farm they are normally cut monthly during the summer months. The leys can be legume-only or more frequently a mixture of legumes and other species, most commonly grasses.

Legume Species Suitable for Green Manures

In most situations, the main factors influencing crop choice are: (i) agronomic performance in terms of establishment and productivity; (ii) compatibility with the existing rotation; and (iii) the composition of the residue which determines the breakdown characteristics of the LGM. However, information on the ability of different species to suppress weeds and timing of flowering may also be important considerations. At a higher level, the issue of whether the sward is cut or grazed also needs to be taken into account, as some species may not tolerate mowing or be compatible with certain livestock. While the majority of species grown in LGMs are forage legumes, some grain legumes are also used. Below is a brief summary of the main legume species grown in LGMs in Europe. Further detailed information may be found in other chapters of this book or is readily available elsewhere, and examples of some common LGMs are shown in [Fig. 8.1](#).

Clovers

Trifolium spp. (clovers) are the legumes most widely used in LGMs. There are many species with different characteristics that can be used in a wide variety of LGMs. They are small annual, biennial or short-lived perennial herbaceous plants with characteristic trifoliate leaves.

Trifolium repens L. (white clover) is commonly used for grazing leys or intercropping. It is very persistent and grows close to the ground. There are many cultivars available and these are characterized by the size of the leaves: small- (e.g. 'Aberystwyth'), medium- (e.g. 'AberDai') and large- (e.g. 'Alice') leaved.

Trifolium pratense L. (red clover) is higher-yielding, less persistent and more drought-tolerant than white clover. It does not grow well at a pH below 5.5. The cultivars are separated into two groups: (i) early types (e.g. 'Merviot') that grow in early spring and most of the yield is from the first cut; and (ii) late types (e.g. 'Britta') that can be used in medium-term leys.

Trifolium incarnatum L. (crimson clover) is a frost-sensitive annual with brightly coloured flowers. Although it does not recover well after cutting, it may

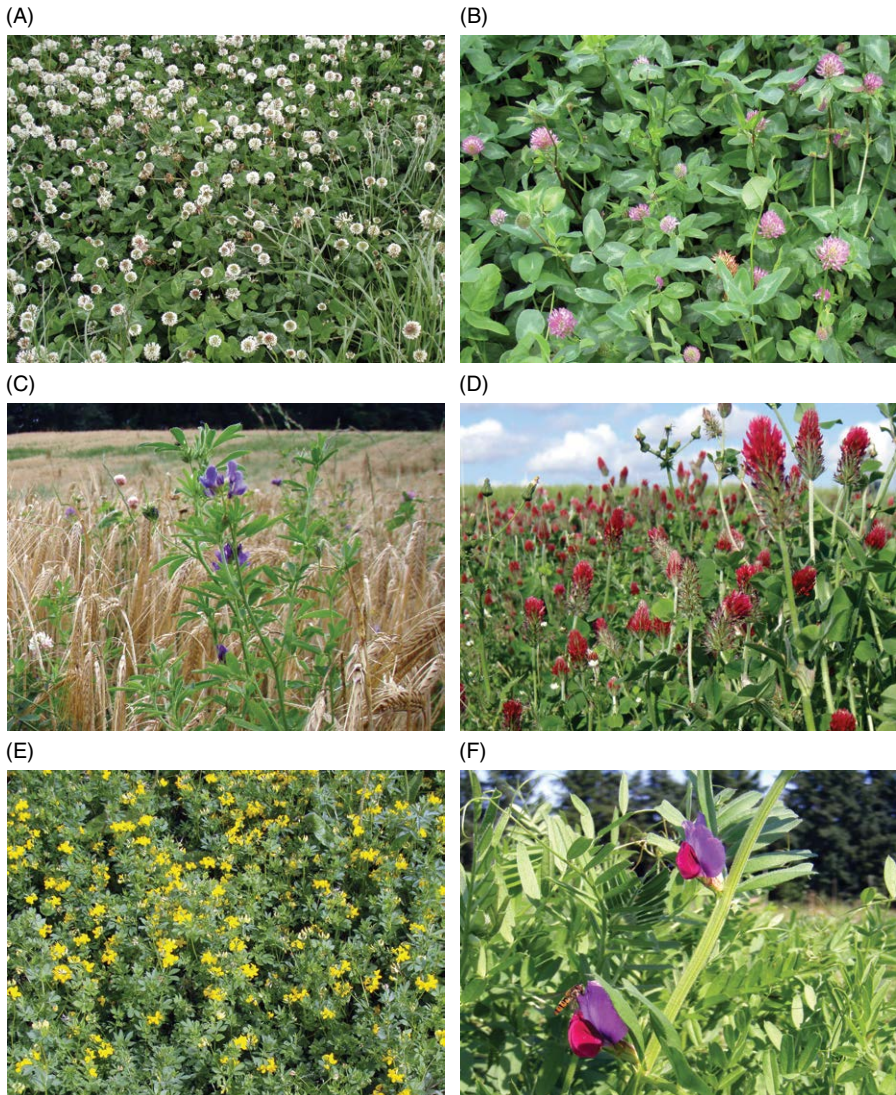


Fig. 8.1. Legume species suitable for green manures. (A) White clover, (B) red clover, (C) lucerne, (D) crimson clover, (E) birdsfoot trefoil and (F) winter vetch. (Photo credits: John Baddeley.)

be used for forage when young. It grows and flowers rapidly from seed so can be used as an early food source for pollinators or as a weed suppressor.

There are several other less widely used clover species that can be useful for LGMs under specific climatic and soil conditions. These include: Alsike clover (*Trifolium hybridum* L.), subterranean clover (*Trifolium subterraneum* L.), strawberry clover (*Trifolium fragiferum* L.), yellow suckling clover (*Trifolium dubium* Sibth.), rose clover (*Trifolium hirtum* All.), Caucasian clover (*Trifolium ambiguum* M. Beeb.) and berseem or Egyptian clover (*Trifolium alexandrinum* L.).

Medics

Medicago is a genus with many similarities to clovers, and two species are widely used in LGMs.

Medicago sativa L. (lucerne or alfalfa) is a large perennial plant with a deep taproot and best known as a forage crop. It prefers a soil pH over 6 in relatively warm and dry climates but can be used in colder areas provided they are not too wet, and can produce the highest annual yield of all forage legumes (up to 15 t/ha). Inoculation of seeds with appropriate rhizobia is usually necessary.

Medicago lupulina L. (black medic) is an annual or short-lived perennial suitable for summer LGMs. It is almost always grown in mixtures and is useful for intercropping due to its low growth habit (10–15 cm). It is not good for grazed systems.

There are several other species of medics (e.g. *Medicago littoralis* Rohde ex Lois., *Medicago tornata* (L.) Mill., *Medicago rugosa* Desr., *Medicago denticulata* Willd., *Medicago minima* (L.) Bart., *Medicago laciniata* (L.) Miller and *Medicago polymorpha* L.) that could be used for LGMs in Mediterranean climates with mild winters.

Vetches

Vicia sativa L. (common vetch or tares) and *Vicia villosa* L. (hairy vetch) are long, trailing annual plants suitable for winter- spring- or summer-sown LGMs. They are protein-rich forage crops, often grown in a mixture with a cereal that provides physical support.

Trefoils

The genus *Lotus* has several species that are grown as LGMs. Their main advantage is that they grow well on soil that is too wet, cold or acid for clovers, and this goes some way to compensate for the generally lower yields of trefoils. Their long, trailing growth habit makes them well suited to mixtures, although they attain high biomass only after many months of growth.

Sweet clovers

Melilotus spp. are biennials that are drought-resistant and tolerant of poor soil conditions, although they prefer warmer climates. These large (up to 2 m tall), productive plants are tolerant of grazing and have a high protein content. Their deep, penetrating root systems can help improve soil structure.

Lupins

There are several lupin species that are grown in LGMs, such as white lupin (*Lupinus albus* L.), bitter blue or narrow-leaved lupin (*Lupinus angustifolius* L.) and

yellow lupin (*Lupinus luteus* L.). They are large annual plants that perform well on poor, light soils and are somewhat tolerant of acidic conditions. Lupins are generally grown in warmer climates and are used for grazing or silage production.

Faba bean and pea

Although most commonly grown for grain, faba bean (*Vicia faba* L.) is a high-biomass overwintering species that can be incorporated during spring or cut down and allowed to regrow before incorporation. There are many cultivars of pea (*Pisum sativum* L.) that can be used in LGMs, but spring cultivars have low tolerance to frost so winter cultivars are recommended in cooler climates. Mixtures of cereals with grain legumes allow the former to physically support the latter. A drawback is that seed costs can be high.

Non-legume companion species

Legume-only stands tend to accumulate, via fixation, high levels of N, some of which is likely to be lost during the winter by leaching. However, if they are mixed with non-legumes that risk is much reduced as the non-legume takes up N. For example, a mixture of clover and grass is as efficient in taking up N from the soil as pure stands of grass, and the green matter contains about as much N late in the autumn as a pure stand of clover (Bergkvist *et al.*, 2011). There is also a grass sink effect (see Humphreys *et al.*, Chapter 9, this volume). When N is lost from the clover during winter, it can be taken up again by the grass as soon as it reassumes growth in the spring. Winter annual legumes can, for the same reason, be mixed with a winter annual cereal crop, such as rye.

Species-rich mixtures of legumes

Most LGMs are relatively simple mixtures of a legume with another species such as a grass or brassica, as described above. While these systems perform well in the right conditions, their reliance on just a few species can be a drawback. Well-designed mixtures of many species of legumes have the potential to mitigate this issue. The legume component especially is susceptible to failure if the weather conditions prevent good establishment or growth. Conditions that are unfavourable for one legume species in the mixture may favour the growth of another. Where a simple mixture is included in a rotation, the lack of variation in chemical composition means that N release to a following arable crop may not be synchronized with the N demands of that crop. However, variations in chemical compositions between species in a complex mixture mean that they decompose at varying rates, leading to a more even supply of N to following crops. Furthermore, species-rich LGMs inherently have the flexibility to be designed, increasing biodiversity and providing a range of desired ecosystem services such as nectar provision for pollinators (Malézieux *et al.*, 2009).

In general, the greater the number of legume species in a mix, the greater the potential to provide a wide range of functions. However, in agricultural situations, there is an inevitable trade-off between these wider functions and the overriding driver of agricultural production. A recent study in the UK concluded that the optimum number of legume species in a mixture for most agricultural purposes is three (Storkey *et al.*, 2015). However, if there are specific goals such as weed suppression then the number of species can be increased. The mix can also be tailored to match soil and environmental conditions. This multifunctionality is an increasingly important aspect of agricultural systems and is more readily delivered by a species-rich LGM than by the main cash crop phases of a rotation.

Crop Management

Establishment

Seeds of many legumes used as green manures are often more expensive than those of non-leguminous green manure crops, so it is important to take steps to ensure optimum conditions for germination and maximum ground cover from the resulting LGM. The first step is the preparation of a good seedbed with a fine tilth and adequate moisture levels prior to drilling or broadcasting. Drilling is a better method for many species, especially those with large seeds such as vetches that are attractive to birds. It enables good control over the depth of sowing. However, mixtures often contain species with a large range of seed sizes and this may be technically difficult to handle with a drill unless multiple passes are made. Broadcasting can address many of the above problems, although seed size range can still be a concern. After broadcast, seed may be incorporated into the soil by light harrowing or rolling.

Successful N fixation by legumes requires the presence of the appropriate strain of rhizobium and this will not always be present in the soil. This is particularly a problem where non-native legumes are grown and can be alleviated by inoculation of the seed before sowing. For example, most lucerne seed sold in the UK is pre-coated with inoculum. Alternatively, inoculum mixes that are added to seeds at sowing are widely available commercially and it is also possible for farmers to produce their own, at least on a small scale.

A further consideration is the availability of suitable seed. Many of the less common species that might be used for LGMs are not produced in large quantities and may suffer from fluctuations in availability. This is particularly true if certified seed is required for organic systems, although derogation for a proportion of a mixture to be non-organic may be possible.

Sowing time

Although the timing of sowing is critically important, it is difficult to give precise guidance as it depends on the combination of climate and species, plus the myriad local conditions that also must be taken into account. In general, most

LGMs perform well if sown in the spring and early summer and are sown after risk of frost has passed but in time to allow good establishment before summer drought restricts growth. In contrast, only a few species of legumes are suitable for autumn sowing in northern Europe. If they are sown too late, the plants may establish poorly or not be large enough to survive winter, but if they are sown too early they can reach their reproductive stage in autumn and lose winter hardiness. In practice, large-seeded species are often the best choice for late sowing as they tend to have a higher relative growth rate, and sowing at a higher seed rate can mitigate establishment issues. In addition to the direct impact of sowing time on plant establishment, consideration must also be given to the necessity to fit in with the sequence of crop rotation, which is discussed later in the chapter.

Fertilization

The amount of legume and the proportion of it in an LGM mixture can largely be determined by management, whereas the amount of any grass during the first growing season can be effectively determined by the seed rate or by the time of undersowing (Ohlander *et al.*, 1996). While these latter factors have some importance for legumes, they are not nearly as important as the amount of N fertilizer used. Many studies have reported a large decrease in the legume component of LGMs when high levels of N are applied (Ohlander *et al.*, 1996; Bergkvist *et al.*, 2011). This effect is species-specific, with, for example, red clover being more tolerant of high N levels than white clover. While many LGMs are grown without fertilizer, this effect should be borne in mind in cases such as intercropping or undersowing where some fertilizer may be applied for the benefit of the accompanying crop.

Cutting and grazing

Unless an LGM is in the ground for only a matter of months or grown as part of an intercrop, some management, in terms of cutting or grazing, will be required. This tends to make the LGM more productive overall and increase the total amount of N fixed (Hatch *et al.*, 2007; Dahlin and Stenberg, 2010). If cutting is carried out, then there is a question of what to do with the clippings. A commonly practised system is 'cut and mulch', where the clippings are left in place. This has the advantages of helping to control weeds and not removing nutrients such as phosphorus (P) and potassium (K) from the system, but N fixation may be reduced due to the process returning relatively N-rich material to the system. Care must also be taken not to let the LGM get too tall before cutting and to use a mower that will chop the clippings, otherwise the crop may be smothered by the cut material. The alternative is to remove the clippings, which may then be sold or used elsewhere for feed or compost. This increases the flexibility to the farmer but risks depletion of soil nutrients in the longer term. Not all legumes are suitable for cutting or must be cut high to avoid removal of aerial buds, making species selection important.

As with cutting, not all legumes are suitable for grazing as their growth habit makes them unable to regenerate well (e.g. crimson clover). Of those that are suitable, some (e.g. white clover and lucerne) can cause bloat in ruminants unless the grazing regime is carefully managed. Alternatively, low-bloat legumes such as birdsfoot trefoil and sainfoin may be grown. Whatever species are sown originally, the species composition will change over time more rapidly in grazed swards than in those that are cut, due to the selectivity of grazers. These problems are usually worth some effort to overcome, as grazed LGMs are capable of delivering greater yields of high-quality, protein-rich forage than grass-only systems, and with a reduced N requirement both during growth and for the following crop (Martens and Entz, 2011).

Incorporation

The method and timing of incorporation of an LGM into the soil are some of the most important processes governing N availability to the following crop. The choice of method is dictated to a certain extent by the choice of species grown and prior management. In anything other than well-grazed swards, the first stage will probably be a reduction in the bulk of the LGM through cutting with a mower or harrow. After the material has dried sufficiently, further incorporation can then take place. Ploughing is a good and commonly used method that is effective. It does not mix plant and soil particularly well, and if done too deeply may retard N release. Harrowing can mix the plant and soil effectively but does not do so to any great depth in the soil. Rotary tillage offers a combination of these processes, but comes at the expense of high power requirements.

In practice, the timing of incorporation is often chosen to fit with farm operations and the agronomic requirements of cash crops in the rotation. Whether spring or autumn, it is important that incorporation happens so that the release of N is synchronized with crop requirements, to avoid the loss of excess N from the system (Cook *et al.*, 2010; Dabney *et al.*, 2010; Campiglia *et al.*, 2011). N losses in the form of N leaching and nitrous oxide (N₂O) emissions dominate, depending on timing of soil incorporation and climatic conditions (Ball *et al.*, 2007; Olesen *et al.*, 2009; Askegaard *et al.*, 2011) and ammonia volatilization may be a particular issue in Mediterranean climates (Rana and Mastrorilli, 1998). These N losses reduce the possible N supply to following crops, and also constitute environmental burdens with N leaching contributing to eutrophication of aquatic ecosystems and N₂O being a potent greenhouse gas.

Effects of Legume Green Manures

Supply of N to following crops

The main agronomic reason for growing LGMs is to add N to the system that can be used by a following cash crop. N accumulated by the LGM is released into the soil after incorporation through the process of mineralization by soil microbes

(Murphy *et al.*, 2004). The rate at which this complex process occurs is governed by many factors such as temperature, moisture availability and the chemical composition (quality) of the LGM residue (Cadisch *et al.*, 1998). Key to this is the ratio of carbon (C) to N, and the form of that C because structural components such as lignin are more resistant to decomposition. As these parameters vary with species, the quality of the LGM residue can be manipulated by the selection of appropriate species. Thus plants with large, N-rich leaves such as red clover will break down more rapidly than woodier species such as mature lucerne, and all legumes decompose faster than grasses.

The amount of N realized by European LGMs depends on a diverse range of factors, and many studies have attempted to quantify it (e.g. Mueller and Thorup-Kristensen, 2001; Cuttle *et al.*, 2003). Overall the results are highly variable, with figures ranging from almost zero to over 500 kg/ha of N. In practice, most LGMs may correspond to fertilizer N applications of up to 100–200 kg/ha. Higher figures tend to be associated with highly managed, shorter-term LGMs whereas more extensive, less managed systems may deliver 50 kg/ha of N or less.

Effects on other soil properties

In addition to the effects on N, the incorporation of LGMs may improve many different indicators of soil quality such as aggregate stability, labile organic matter and soil faunal activity (Biederbeck *et al.*, 1998; Birkhofer *et al.*, 2011). Some of these changes, especially in soil organic matter, may only be evident in the long term (Stobart and Morris, 2011; O’Dea *et al.*, 2013).

The growth and incorporation of an LGM can enhance biological P cycling in soil and improve the dissolution and bioavailability of soluble phosphate rock (Barea *et al.*, 2002). Changes in the soil pH following the growth of an LGM can also increase availability of P and K, while reducing losses due to runoff and leaching (e.g. Scott and Condon, 2003). In grass/clover leys, there is high absorption of K, probably due to the combination of shallower and deeper roots of the two crop species.

Rotational Considerations

As there is often no direct economic gain from the growth of LGMs, it is important that they are as productive as possible and compatible with the main cash crops that will be grown. The cash crops grown may place restrictions on which legume species are grown, and set the schedule for their planting and incorporation. It is vital that a proper assessment is made of the likely N input from the LGM, so that the amount of any supplementary N can be calculated accurately. Finally, an economic assessment reveals the financial implications of the choices made.

In northern Europe, white and red clover, the most frequently used legume species in LGMs, are often undersown in spring into crops of spring cereals. If they are sown in autumn in areas with cold and long winters, such as in Scandinavia, their sowing time needs to be early enough so they can survive the winter (Laidlaw

and McBride, 1992; Brandsæter *et al.*, 2002). Winter crops, such as wheat and rye, yield highest after sowing in September and undersown legumes would generally not survive winter if sown much later. Further south, in Germany and the southern UK, clover species can be sown with winter cereals in autumn and still survive winter (e.g. Heyland and Merkelbach, 1991).

Legumes alone or mixed with cereals or brassicas are the most common species cultivated in southern areas of Europe as LGMs. In addition to the typical species grown for forage or grain (e.g. faba bean, vetch or clover) other legumes such as narbon vetch (*Vicia narbonensis* L.) or lupins may be used. In areas with hot, dry summers, where water competition with the main crop is possible, LGMs are avoided during the summer and limited to cover the soil in olive groves or vineyards during the winter season.

After the harvest of the main crop, an undersown LGM is left to grow during autumn and can be incorporated before winter, in early spring before sowing of a spring crop or in the summer before sowing of an autumn-sown crop. It is generally only organic farmers that let the LGM grow for a whole summer to control weeds by repeated mowing and to add N to the system. In northern Europe, however, it has recently become less common for LGMs to be grown only for fixing N and to control weeds. Generally, farmers who have no use of the LGM as fodder will sell the green biomass, although this will reduce the beneficial effects to the following crop.

Winter annual legumes (e.g. vetch) may be sown after harvest of one crop in July or in the beginning of August. The following spring they are incorporated or grown on to become living or dead mulch for a spring crop, to provide it with N and to control small-seeded weeds. The major part of the growth and N fixation will occur during spring, so autumn incorporation is not the best option. An important feature of autumn-sown LGMs is that they are unlikely to fix significant quantities of N unless they are allowed to grow through the following summer, which is likely only in organic systems. If a green manure is required purely for the overwinter period, then one without legumes may be a more flexible option.

N budgets

Given that one of the main reasons that LGMs are grown is the input of N they provide to the system, it is vital that this input is taken into account when considering what further additions of N may be required for a following crop. This is problematic, as it is the result of interactions between many complex processes that control both the amount of N fixed and the amount transferred to a following crop, as detailed above. While the effects of changes in any one parameter in isolation are generally well known and predictable, forecasting in a field-based system with many uncontrolled variables is challenging. One approach is the use of computer-based models and many of these are now available. Some are aimed at the scientific user and require detailed knowledge of many variables. Others are designed to be used by farmers and advisors, such as the FBC model (Cuttle, 2006) and later versions of NDICEA (van der Burgt *et al.*, 2006), which require relatively

simple inputs that farmers are likely to know or can easily assess, to produce guidance as to the amount of N available from LGMs.

Economics

The economic impact of growing LGMs is highly dependent on the design of the system. Whether the LGM is grown as a main crop, as an undersown crop or as an intercrop, the gross margin of the whole crop rotation has to be considered because of the positive internal effects of legumes (listed below). This is due to the simple sum of the individual gross margins of the cash crops with the variable costs of the LGM crops (Weitbrecht and Pahl, 2000).

An important effect of an LGM is the potential reduction of the use of synthetic N fertilizer. One way to assess the economic benefits is therefore to compare the costs of N fixed from the LGM and the costs of N of mineral fertilizers. The price of N gained by LGMs can be calculated from their N profit and their variable costs. The variable costs of an LGM depend mainly on the seed costs, establishment and management costs. Since these costs are relatively high, the resulting price of the N is higher than that from synthetic fertilizer (Knight *et al.*, 2010).

To consider all internal effects it is recommended that the total gross margin of the whole crop rotation is considered. If an LGM replaces a main cash crop, the financial loss of not growing this crop has to be included in the calculation as foregone revenue, together with the variable costs of the LGM (seed, establishment and management). These are the total costs to be considered for the integration of the LGM.

An LGM significantly increases the yield of the subsequent crop (Knight *et al.*, 2010). The resulting gain in value of the following crop must be considered, but is highly dependent on the market price. In addition, the savings made in N fertilizers, pesticides and soil cultivation to the following crop have to be taken into account in the calculation.

In conclusion, the economic benefits of LGMs depend mainly on the costs of the LGM, on the value of the replaced crop and any gains in the subsequent crop. The ratio of these costs and gains determines whether growing an LGM results in a financial benefit. It is also important to remember that LGMs may have many additional effects such as the supply of additional on-farm fodder, which can be included in an economic analysis, or an impact on soil erosion which is difficult to quantify economically.

Conclusion

LGMs are widely used across Europe in a diverse range of cropping systems. Significant regional variations mean that they are optimized for local growing conditions and patterns of crop rotations. LGMs are key to successful organic systems, in which a significant part of the crop rotation is often devoted to their growth. Due to rising costs of synthetic inputs and concerns over the environmental performance of agriculture, there is increased interest in expanding the use of LGMs

in non-organic systems. Although the traditional focus has been on the supply of N, they have a wide range of potential benefits that include improving soil quality, reducing soil erosion and increasing the biodiversity of farmland. However, LGMs will not be agronomically or economically viable in all systems and in these cases other types of green manures may be more appropriate. As demand for multi-functional agricultural systems grows, and is increasingly required by European agricultural policies, so does the potential for greater use of LGMs.

References

- Askegaard, M., Olesen, J.E., Rasmussen, I.A. and Kristensen, K. (2011) Nitrate leaching from organic arable crop rotations is mostly determined by autumn field management. *Agriculture Ecosystems and Environment* 142, 149–160.
- Ball, B.C., Watson, C.A. and Crichton, I. (2007) Nitrous oxide emissions, cereal growth, N recovery and soil nitrogen status after ploughing organically managed grass/clover swards. *Soil Use and Management* 23, 145–155.
- Barea, J.M., Toro, M., Orozco, M.O., Campos, E. and Azcon, R. (2002) The application of isotopic ((32)P and (15)N) dilution techniques to evaluate the interactive effect of phosphate-solubilizing rhizobacteria, mycorrhizal fungi and *Rhizobium* to improve the agronomic efficiency of rock phosphate for legume crops. *Nutrient Cycling in Agroecosystems* 63, 35–42.
- Bergkvist, G., Stenberg, M., Wetterlind, J., Bath, B. and Elfstrand, S. (2011) Clover cover crops under-sown in winter wheat increase yield of subsequent spring barley – effect of N dose and companion grass. *Field Crops Research* 120, 292–298.
- Biederbeck, V.O., Campbell, C.A., Rasiyah, V., Zentner, R.P. and Wen, G. (1998) Soil quality attributes as influenced by annual legumes used as green manure. *Soil Biology and Biochemistry* 30, 1177–1185.
- Birkhofer, K., Diekötter, T., Boch, S., Fischer, M., Müller, J., Socher, S. and Wolters, V. (2011) Soil fauna feeding activity in temperate grassland soils increases with legume and grass species richness. *Soil Biology and Biochemistry* 43, 2200–2207.
- Brandsæter, L.O., Olsmo, A., Tronsmo, A.M. and Fykse, H. (2002) Freezing resistance of winter annual and biennial legumes at different development stages. *Crop Science* 42, 437–443.
- Cadisch, G., Handayanto, E., Malama, C., Seyni, F. and Giller, K.E. (1998) N recovery from legume prunings and priming effects are governed by the residue quality. *Plant and Soil* 205, 125–134.
- Campiglia, E., Mancinelli, R., Radicetti, E. and Marinari, S. (2011) Legume cover crops and mulches: effects on nitrate leaching and nitrogen input in a pepper crop (*Capsicum annuum* L.). *Nutrient Cycling in Agroecosystems* 39, 399–412.
- Cook, J.C., Gallagher, R.S., Kaye, J.P., Lynch, J. and Bradley, B. (2010) Optimizing vetch nitrogen production and corn nitrogen accumulation under no-till management. *Agronomy Journal* 102, 1491–1499.
- Cuttle, S.P. (2006) Development of the FBC model to estimate the nitrogen available from fertility-building crops in organic rotations. *Aspects of Applied Biology* 79, 259–262.
- Cuttle, S., Shepherd, M. and Goodlass, G. (2003) A review of leguminous fertility-building crops, with particular reference to nitrogen fixation and utilisation. Department for Environment, Food and Rural Affairs (Defra) Project Report OF0316: The development of improved guidance on the use of fertility-building crops in organic farming Defra, London.
- Dabney, S.M., Delgado, J.A., Meisinger, J.J., Schomberg, H.H. and Liebig, M.A. (2010) Using cover crops and cropping systems for nitrogen management. In: Delgado, J.A. and Follett, R.F. (eds) *Advances in Nitrogen Management for Water Quality*. Soil and Water Conservation Society, Ankeny, Iowa, pp. 231–282.

- Dahlin, A. and Stenberg, M. (2010) Transfer of N from red clover to perennial ryegrass in mixed stands under different cutting strategies. *European Journal of Agronomy* 33, 149–156.
- Hatch, D.J., Goodlass, G., Joynes, A. and Shepherd, M.A. (2007) The effect of cutting, mulching and applications of farmyard manure on nitrogen fixation in a red clover/grass sward. *Bioresource Technology* 98, 3243–3248.
- Heyland, K.U. and Merkelbach, H. (1991) Die Möglichkeiten des Einsatzes von Untersaaten zur Unkrautunterdrückung sowie Konkurrenzwirkungen von Unkraut und Untersaat auf die Ertragsbildung des Winterweizens. *Bodenkultur* 42, 347–359.
- Knight, P., Lacey, T., Heading, E., Will, T., Rayns, F. and Rosenfeld, A. (2010) Extension of FV 299 – investigation into the adoption of green manures in both organic and conventional rotations to aid nitrogen management and soil structure. Final report of Horticultural Development Council project FV299a. Available at: http://horticulture.ahdb.org.uk/sites/default/files/research_papers/FV_299a_Final_report_2010.pdf (accessed 18 October 2016).
- Laidlaw, L.S. and McBride, J. (1992) The effect of time of sowing and sowing method on production of white clover in mixed swards. *Grass and Forage Science* 47, 203–210.
- Malézieux, E., Crozat, Y., Dupraz, C., Laurans, M., Makowski, D., Ozier-Lafontaine, H., Rapidel, B., de Tourdonnet, S. and Valantin-Morison, M. (2009) Mixing plant species in cropping systems: concepts, tools and models. A review. *Agronomy for Sustainable Development* 29, 43–62.
- Martens, J.R.T. and Entz, M.H. (2011) Integrating green manure and grazing systems: a review. *Canadian Journal of Plant Science* 91, 811–824.
- Mueller, T. and Thorup-Kristensen, K. (2001) N-fixation of selected green manure plants in an organic crop rotation. *Biological Agriculture and Horticulture* 18, 345–363.
- Murphy, D.V., Stockdale, E.A., Hoyle, F.C., Smith, J.U., Fillery, I.R.P., Milton, N., Cookson, W.R., Brussaard, L. and Jones, D.L. (2004) Matching supply with demand. In: Hatch, D.J., Chadwick, D.R., Jarvis, S.C. and Roker, J.A. (eds) *Controlling Nitrogen Flows and Losses, Proceedings of the 12th International Nitrogen Workshop*, Exeter, UK, 21–24 September 2003, pp 101–112.
- O’Dea, J.K., Miller, P.R. and Jones, C.A. (2013) Greening summer fallow with legume green manures: on-farm assessment in north-central Montana. *Journal of Soil and Water Conservation* 68, 270–282.
- Ohlander, L., Bergkvist, G., Stendahl, F. and Kvist, M. (1996) Yield of catch crops and spring barley as affected by time of undersowing. *Acta Agriculturae Scandinavica Section B – Soil and Plant Science* 46, 161–168.
- Olesen, J.E., Askegaard, M. and Rasmussen, I.A. (2009) Winter cereal yields as affected by animal manure and green manure in organic arable farming. *European Journal of Agronomy* 30, 119–128.
- Pieters, A.J. (1927) *Green Manuring Principles and Practice*. Wiley, New York.
- Rana, G. and Mastroianni, M. (1998) Ammonia emissions from fields treated with green manure in a Mediterranean climate. *Agricultural and Forest Meteorology* 90, 265–274.
- Scott, J.T. and Condon, L.M. (2003) Dynamics and availability of phosphorus in the rhizosphere of a temperate silvopastoral system. *Biology and Fertility of Soils* 39, 65–73.
- Stobart, R.M. and Morris, N.L. (2011) New Farming Systems Research (NFS) project: long term research seeking to improve the sustainability and resilience of conventional farming systems. *Aspects of Applied Biology* 113, 15–23.
- Storkey, J., Döring, T., Baddeley, J., Collins, R., Roderick, S., Jones, H. and Watson, C. (2015) Engineering a plant community to deliver multiple ecosystem services. *Ecological Applications* 25, 1034–1043.
- van der Burgt, G.J.H.M., Oomen, G.J.M., Habets, A.S.J. and Rossing, W.A.H. (2006) The NDICEA model, a tool to improve nitrogen use efficiency in cropping systems. *Nutrient Cycling in Agroecosystems* 74, 275–294.
- Weitbrecht, B. and Pahl, H. (2000) Lohnt sich der Anbau von Körnerleguminosen? [Is growing pulse crops economical?] *Ökologie und Landbau* 116, 39–41.

9

White Clover Supported Pasture-based Systems in North-west Europe

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Abstract

White clover (WC) (*Trifolium repens* L.) is a useful component of European grasslands due to: (i) its capacity to convert dinitrogen (N₂) gas to plant-available nitrogen (N) in the soil via biological nitrogen fixation (BNF); (ii) its tolerance of grazing; and (iii) its high nutritive value for ruminant livestock. Its relative importance has declined in recent decades in line with the intensification of ruminant production systems that increasingly rely on maize silage and intensively fertilized grass leys. There are many challenges in managing WC on farms. These include: (i) maintaining the ideal balance between the grass and WC in grassland; (ii) low and inconsistent dry matter (DM) productivity; (iii) difficulties with ensilage due to the low herbage DM and sugar concentrations; and (iv) increased risk of bloat. However, the cost of fertilizer N has increased substantially since the late 1990s, particularly relative to the farm-gate price received for milk, beef and sheep meat. This price:cost squeeze has generated renewed interest in the use of WC on farms. Furthermore, under legislation stemming from the Nitrates Directive, permissible stocking densities and rates of fertilizer N input are lower than previously in many European countries, and the lower productivity of WC-rich grassland is not as much of an obstacle to adoption on farms as it has been in the past. As well as the capacity that WC has to improve herbage nutritive value, the main advantage of WC-based systems stems from the replacement or reduction of fertilizer N input by BNF and the contribution that this makes to farm profitability and

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environmental performance. Although WC-rich grassland has lower productivity, lower fertilizer N costs can largely close the gap in farm profitability between WC-based and more intensively managed systems. There is generally less N circulating within lower stocked WC-based systems, resulting in lower N losses to water and lower ammonia and methane emissions to the atmosphere; losses that are often closely related to stocking density. WC has additional advantages when it comes to the other greenhouse gases: nitrous oxide and carbon dioxide. Direct emissions of nitrous oxide are lower from WC-rich grassland than from N-fertilized grassland at the same level of productivity and substantially lower than intensively fertilized grassland. Emissions of carbon dioxide associated with the manufacture, transport and application of nitrogenous fertilizers are avoided by the use of WC. Using life cycle assessment, studies have shown that WC-based systems have between 11% and 26% lower carbon footprint per litre of milk than N fertilized systems; the largest difference was with more intensive systems reliant on high input of fertilizer N. Escalating fertilizer N costs have improved the profitability of using WC in pasture-based systems in recent years. From the perspective of the overall future sustainability of pasture-based ruminant production, WC-based systems offer economic competitiveness, lower energy dependency and lower environmental impact.

Introduction

White clover (WC) (*Trifolium repens* L.) is a useful component of European grasslands due to: (i) its capacity to convert dinitrogen (N₂) gas to plant-available nitrogen (N) in the soil via biological nitrogen fixation (BNF); (ii) its suitability for grazing; and (iii) its high nutritive value for ruminant livestock. It is most commonly grown in association with perennial ryegrass (PRG) (*Lolium perenne* L.) where it can improve sward crude protein, organic matter digestibility, herbage production and herbage intake by ruminants. However, the use of WC has declined in recent decades in line with the intensification of ruminant production systems that increasingly rely on maize silage and intensively fertilized grass leys (Peyraud *et al.*, 2009). There are many challenges to WC management on farms, such as: (i) maintaining the ideal balance between grass and WC in pastures; (ii) low and inconsistent productivity; (iii) increased risk of bloat in grazing livestock; and (iv) difficulties with ensilage.

The productivity of WC-rich grassland that does not receive fertilizer N in pasture-based dairy systems has generally been found to be 70–90% of that of intensively N-fertilized PRG-based grassland (hereafter referred to as grass-only) receiving annual applications of up to 415 kg/ha of fertilizer N (Humphreys *et al.*, 2009; Andrews *et al.*, 2007; Table 9.1). In many countries in the north-west of Europe, these very high rates of fertilizer N input and associated stocking densities are no longer permissible due to regulations under the Nitrates Directive (European Council, 1991). Furthermore, since the late 1990s, the farm-gate cost of fertilizer N has increased at an annual rate of around 5%. Hence, there has been a strong increase in the cost of fertilizer N relative to the farm-gate price received for milk (Fig. 9.1). These trends have negative impacts on the profitability of pasture-based systems of dairy production that rely on high inputs of fertilizer N. At the same time, there has been more regulatory pressure to lower N losses to water and to the atmosphere. These include various national regulations stemming from the

Table 9.1. The number of years that comparisons took place, stocking densities of dairy cows, annual fertilizer N input, concentrates fed to cows, annual herbage production and milk production in systems-scale comparisons of milk production from white clover (WC)-based and N-fertilized grassland.

No. years	Stocking density (LU/ha)	Fertilizer N input (kg/ha)	WC content of herbage (g/kg DM)	Concentrates fed		Herbage production (t DM/ha)	Milk production		References
				(kg/cow)	(kg/ha)		(kg/cow)	(t/ha)	
1	3.86	0	270	211	815	16.25	3468	13.39	Bryant <i>et al.</i> (1982) ^a
	3.86	86	270	211	815	16.11	3500	13.51	
1	4.09	0	230	245	1002	16.97	3196	13.07	Bryant <i>et al.</i> (1982) ^a
	4.09	137	195	245	1002	18.08	3377	13.81	
6	na ^b	0	150	na	na	na	na	8.56	Weissbach and Ernst (1994) ^c
	na	308	na	na	na	na	na	14.20	
5	2.52	122	385	600	1512	na	4224	10.64	Ryan (1986, 1989) ^d
	3.20	361	< 50	600	1920	na	4068	13.02	
3	4.5	0	580	890	4007	8.8	3914	17.61	Aaes and Kristensen (1994) ^e
	5.1	240	260	890	4539	12.1	3965	20.22	
5	3.30	0	152	na	na	16.38	3953	12.96	Ledgard <i>et al.</i> (1998, 1999, 2001) ^f
	3.30	215	107	na	na	18.45	4735	15.52	
	3.30	413	49	na	na	20.58	4858	15.92	
3	1.90	17	290	1847	3509	10.10	8294	15.75	Schils <i>et al.</i> (2000a, b) ^g
	2.20	208	<50	1828	4022	10.80	8095	17.80	
3	4.7	0	504	1008	4738	9.0	4039	18.98	Søegaard <i>et al.</i> (2001) ^e
	4.8	300	0	1008	4838	11.1	4055	19.46	
1	1.90	0	253	1096	2082	9.24	5719	10.87	Leach <i>et al.</i> (2000) ^h
	2.40	350	9	1412	3389	10.35	5724	13.74	
2	1.75	80	240	535	936	10.57	6550	11.46	Humphreys <i>et al.</i> (2008) ⁱ
	2.10	180	39	535	1124	10.75	6275	13.18	
	2.50	248	20	535	1338	12.06	6242	15.61	
	2.50	353	7	535	1338	13.26	6375	15.94	
4	2.15	90	219	531	1142	11.51	6521	14.02	Humphreys <i>et al.</i> (2009) ⁱ
	2.15	226	60	520	1118	12.45	6526	14.03	

Continued

Table 9.1. Continued.

No. years	Stocking density (LU/ha)	Fertilizer N input (kg/ha)	WC content of herbage (g/kg DM)	Concentrates fed		Herbage production (t DM/ha)	Milk production		References
				(kg/cow)	(kg/ha)		(kg/cow)	(t/ha)	
2	1.6	0	240	539	857	8.80	6388	10.20	Keogh <i>et al.</i> (2010) ⁱ
2	2.12	100	180	575	1218	10.10	6273	13.30	
3	2.12	100	210	496	1052	11.10	6137	13.01	Phelan <i>et al.</i> (2013b) ⁱ
1	na	260	200	154	na	13.16	3880	na	Enriquez-Hidalgo <i>et al.</i> (2014) ^j
	na	260	0	154	na	13.05	3728	na	

LU, Livestock unit; DM, dry matter.

^aBryant *et al.* (1982) – Calving in late winter and cows were milked at pasture. Rotational grazing. Lactation length was largely determined by pasture supply.

^bna, Data not available.

^cNo significant differences in concentrates fed per cow (4 kg/cow/day) or in milk production per cow (22.3 kg fat corrected milk/day).

^dCalving in late winter; grazing season from 9 April to 20 October. Rotational grazing. No fertilizer N was applied to the WC-based swards used for grazing; fertilizer N was applied to a non-WC silage area on the low fertilizer N input system. WC content refers to the WC content of the WC-based swards in late summer only.

^eGrass–arable systems with continuous grazing.

^fLedgard *et al.* (1998, 1999, 2001) – Calving in late winter and cows were milked for 250–290 days at pasture. Rotational grazing. Minimal amounts of concentrate supplementation were fed to cows.

^gSchils *et al.* (2000a, b) – Calving from October to April; grazing season from first week of April to last week of October.

^hLeach *et al.* (2000) – Results from final year of a 3-year experiment. Autumn calving; cows dry during much of the grazing season that extended from late spring to mid-October. Nine days later turnout in spring on the WC-based swards.

ⁱCompact calving during 12-week period in spring with a mean calving date in mid-February, cows turned out to pasture as they calved from late January onwards and remained at pasture until late November depending on ground conditions. Rotational grazing. Milk was produced until mid-December each year.

^jMean calving date 19 February. Results presented from 17 April until 31 October 2011. Rotational grazing.

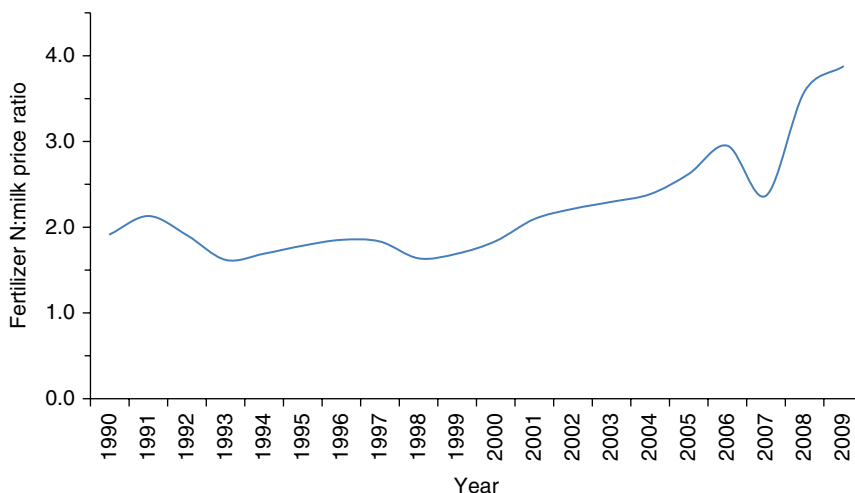


Fig. 9.1. Changes in the fertilizer N:milk price ratio in Western Europe (EU-15) between 1990 and 2011. The data are derived from Eurostat 'purchase prices of the means of agricultural production' and 'selling price of agricultural goods'. (From Eurostat, 2013.)

Nitrates Directive, the Water Framework Directive, the National Emission Ceilings Directive and the European Commission (EC) Climate and Energy Package (European Council, 1991; European Parliament and Council, 2000, 2001). In general, WC-based systems are associated with lower stocking densities, higher N use efficiency, lower surplus N per ha, lower losses of nitrate to water and emissions of ammonia and nitrous oxide (a potent greenhouse gas (GHG)) to the atmosphere than N-fertilized grass-based systems. These differences can be largely attributed to lower N fluxes associated with the generally lower productivity of WC.

In studies of dairy production systems conducted during the 1980s and 1990s, the net margin per hectare of WC-based systems was between 65% and 95% that of intensively fertilized grassland. More recent analyses have found that the difference in net margin per hectare between WC and grass-only systems was not clear cut (Humphreys *et al.*, 2012). It was concluded that if the 1990–2010 trend in fertilizer N and milk prices continued, the WC-based system would become an increasingly more profitable alternative to intensive N fertilizer use for pasture-based dairy production. There is also evidence of increasing interest in the use of WC on farms, for example 50% of sown pastures in the west of France in 2009 were composed of a mix of grasses and WC compared with less than 10% in 1985 (Peyraud *et al.*, 2009).

The purpose of this review is to examine the potential for using WC in pasture-based systems in Western Europe in the context of rising fertilizer N costs and recently implemented environmental regulations curtailing fertilizer N use and stocking densities on farms. The review will identify the potential of WC to contribute to the future sustainability of ruminant production systems, the challenges that currently impede the use of WC in those systems and newly emerging solutions to those challenges.

BNF and Herbage Production

The quantity of reactive N fixed in temperate pastures with WC varies from 10 kg/ha to 300 kg/ha (Andrews *et al.*, 2007; Ledgard *et al.*, 2009), depending mainly on management factors that affect sward WC content. In general, potential herbage production from WC-based systems can be as high as from grassland grown with high rates of fertilizer N input. However, high rates of fertilizer N input generally have a negative impact on BNF as a result of the gradual decline of sward WC content and WC fixation activity. For example, in a 5-year study in Germany, fertilizer N input reduced sward WC content under a wide range of grazing/cutting management systems (Trott *et al.*, 2004). A 2-year study in Ireland carried out as part of the Legume Futures project found a reduction in WC fixation activity to be the most important factor reducing BNF in grassland receiving fertilizer N. Annual fertilizer N inputs of 86 kg/ha, 140 kg/ha and 280 kg/ha reduced BNF by 19%, 17% and 41%, respectively, relative to WC pastures receiving no fertilizer N (Burchill *et al.*, 2014). Meta-analysis of the effect of N fertilizer on WC content and BNF across a range of experiments revealed an exponential reduction in annual pasture WC content in response to annual fertilizer N inputs (Phelan, 2013). From 0 kg/ha to 200 kg/ha, the response is generally linear with a 1.5% reduction in WC content for every 10 kg additional fertilizer N input (Fig. 9.2). The main economic motivation for the inclusion of WC in swards is BNF, so maintaining the WC component of the sward for this purpose is an important aspect of sward management. For this reason, WC swards often receive no or relatively low inputs of fertilizer N, applied only in spring when the contribution of BNF to sward supply is low.

In temperate regions, the WC content of swards usually undergoes a typical cycle in the growing season that complements the growth of PRG. WC content tends to be relatively low in spring. It tends to increase steadily during late spring and summer to reach the highest levels during late summer and autumn, and decline again during the winter although this annual trend is influenced by management (Figs 9.3 and 9.4).

The seasonal fluctuations in WC content and BNF described above mean that some fertilizer N input may be necessary to increase herbage production in early spring, before BNF contributes substantially to sward growth. In the Netherlands, Schils *et al.* (2000a, b) found that WC-based grassland receiving fertilizer N input of 17 kg/ha in spring produced 95% of the herbage of a grass-only swards receiving annual fertilizer N input of 208 kg/ha. Likewise in Ireland, Humphreys *et al.* (2009) showed that WC-based pastures receiving between 80 kg/ha and 90 kg/ha of fertilizer N in spring had herbage production that was 92% of grass-only pastures receiving 226 kg/ha of N and 80% of grass-only pastures receiving 353 kg/ha.

As well as variation in BNF within years, there can also be considerable variation in BNF from year to year. For example, Burchill *et al.* (2014) found a two- to threefold difference in BNF between consecutive years. Therefore, while WC can make a valuable contribution to the availability of plant-available N in the soil, both the within- and between-year variation in the supply of N from this source creates challenges at farm level for the management of BNF and N nutrition of grassland. Management of BNF is mediated most directly through the management

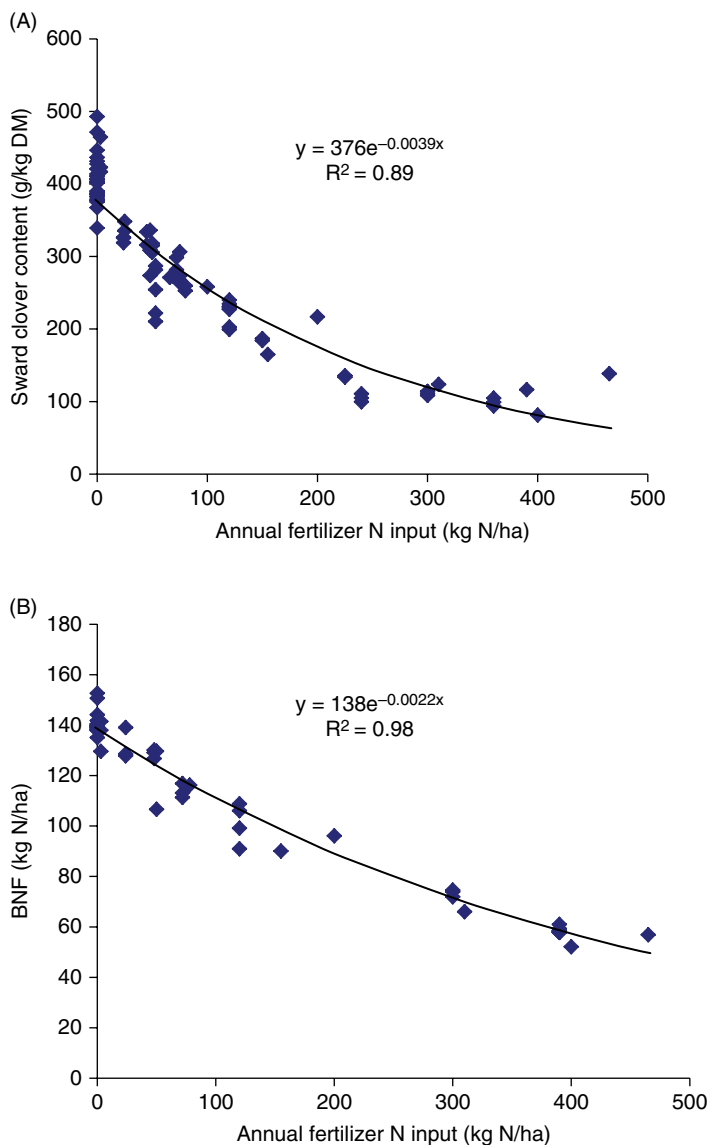


Fig. 9.2. Meta-analysis of the effects of annual fertilizer N input on (A) annual sward white clover (WC) content and (B) annual biological nitrogen fixation (BNF) in grass-WC swards ($P < 0.001$ in both cases). DM, Dry matter. (From Phelan, 2013.)

of WC in the sward. As BNF increases soil N over time, the grass component becomes more competitive and maintaining WC content of the sward can become difficult. This is generally not a major problem in temporary grass-arable rotations because soil N tends to be low after a sequence of arable crops and when soil N increases and WC content declines, it can simply be cultivated for arable production again. In permanent grassland, declining WC contents are more difficult to

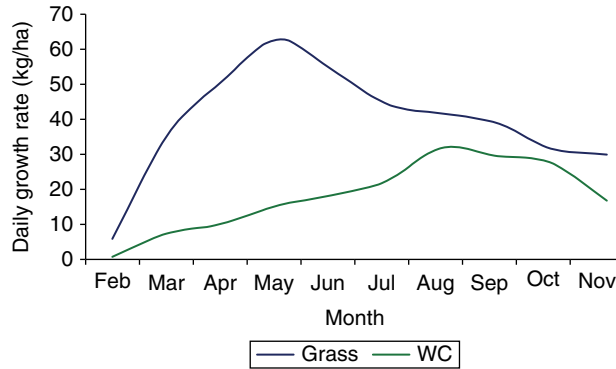


Fig. 9.3. Grass and white clover (WC) growth rates throughout the growing season in Ireland.

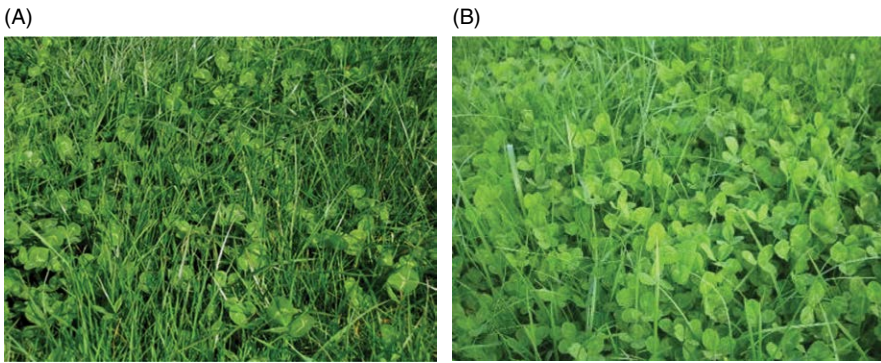


Fig. 9.4. Clover during April (A) and estimated to be 35–45% of dry matter in August (B).

manage and it is the lack of consistency of WC BNF from year to year that largely accounts for the general unpopularity of WC for permanent pastures in Western Europe.

Nutritive Value and Milk Production

WC herbage has higher nutritive value than PRG herbage and is preferentially grazed by dairy cows. This can increase cows' voluntary dry matter (DM) intake and consequently milk production. This increase can be attributed to a lower cell wall content and different cell wall characteristics of WC compared with grass (i.e. both a lower resistance of the WC herbage to chewing and higher rates of particle breakdown, digestion and passage rate through the rumen, leading to higher intake) (Steg *et al.*, 1994). Higher herbage intakes and higher milk yields of the WC-rich swards can also be attributed to higher crude protein concentration in the herbage DM. However, where fertilizer N use is not limited and where sward crude protein content is therefore high, very high WC contents

(400–500 g/kg DM) are required to get an increase in milk output per cow over that obtained from grass only.

Such high WC contents are rare. None of the systems-scale studies presented in Table 9.1 recorded a significant difference in milk output per cow between the WC-rich and N-fertilized grass-only grassland, because the WC content of herbage DM was typically not high enough to increase milk yield per cow. Even high WC content in grass-arable systems did not contribute to an improvement in milk output per cow (Aaes and Kristensen, 1994; Søgaard *et al.*, 2001). It is unlikely that WC sward contents of 400–500 g/kg DM can be sustained in permanent, grazed WC-based grassland at the farm scale except for short periods during the late summer and early autumn. Therefore the use of WC compared with fertilized grass generally has little or no impact on milk output per cow over the course of an entire grazing season or entire lactation.

Management

The main economic motivation for inclusion of WC in grazed grassland is BNF. For a given site, the extent of BNF depends primarily on the WC content of herbage. Therefore an important aspect of managing WC in grassland is maintaining a high WC content throughout the year and from year to year. Grassland management entails multiple objectives such as: (i) maximizing nutritive value; (ii) maximizing herbage production; (iii) budgeting grassland areas to extend the grazing season length; (iv) maintaining a desirable sward structure; (v) protection of the soil; and (vi) maintaining the persistency of desirable botanical components of the sward from year to year. Sophisticated management guidelines have been developed to achieve the optimum balance between these multifaceted objectives, primarily for N-fertilized grass-only swards. Effective implementation at farm level requires training and skill. Indeed, one of the reasons for the decline in grazing on dairy farms in Western Europe is that indoor feeding systems reliant principally on maize silage, grass silage and purchased concentrates are simpler to implement at farm level, particularly where farms are fragmented into separate land parcels. Inclusion of WC in swards and maintaining the balance between species to ensure optimum WC content within years and from year to year substantially increases the complexity of grassland management.

Length of the grazing season

In WC-based pastures, herbage production is slower to commence at the end of winter than in grass-only pastures, particularly on cold, heavy soils. Optimum growth rates of WC are at temperatures between 20°C and 30°C, whereas those of PRG are 15°C–20°C. Therefore WC-based pastures can produce more biomass in summer than grass-only pastures, depending on the level of fertilizer N input.

In the typical Irish system of dairy production, compact calving and early turnout to pasture in spring brings clear economic advantages. WC-based swards receiving no input of fertilizer N have poor spring growth and relatively poor yields of

first-cut silage (Frame and Newbould, 1986). Fertilizer N can be applied in spring at rates of 50–70 kg/ha to give improved production in spring without affecting annual production of WC-based swards (Laidlaw, 1980), although it can cause a lower WC content in swards later in the growing season (Frame and Boyd, 1987).

Post-grazing height under rotational grazing

Simulated grazing experiments have found that lowering defoliation height during the main growing season on WC-based grassland generally increases WC content, WC herbage production and total herbage production. While tighter grazing can have a positive impact on herbage yields, lowering the post-grazing height to 4 cm with WC-based swards did not affect annual milk yield under rotational grazing compared with post-grazing heights of 5 cm and 6 cm (Phelan *et al.*, 2013a). Both BNF and herbage production were higher with the tighter grazing treatment in the latter experiment. A post-grazing height of 4 cm is therefore recommended for WC-based grassland under rotational grazing.

Continuous versus rotational grazing

Under continuous grazing (set-stocking), managing sward height is more complex as it is a result of grazing pressure (the balance between herbage production and demand), so it reflects both grazing frequency and grazing severity. However, lower sward heights are associated with higher sward WC contents. Gibb *et al.* (1997) found that under continuous grazing, maintaining a sward height of 7 cm achieved higher intake rates in dairy cows than heights of either 5 cm or 9 cm.

Rotational grazing generally promotes sward WC contents better than continuous grazing. Hay *et al.* (1989) compared WC-based swards grazed with ewes either rotationally or continuously in New Zealand and found that the rotationally grazed swards had higher mean annual WC content (26% compared with 6%) and stolon DM mass (46 g/m² compared with 14 g/m²). Davies (2001) reported that switching from continuous to rotational grazing caused an increase in WC content and WC stolon size, and Harris (1987) reported that allowing a continuously grazed sward a rest of 1 month in late summer/autumn could increase WC content five- to tenfold. Therefore, rotational or strip grazing should generally be used on WC-based pastures. If continuous grazing is used, a rest (ungrazed) period can increase WC content.

Cutting versus grazing

WC-based swards tend to be relatively more productive under cutting than under grazing regimes, because cutting tends to deplete soil N reserves, which increases BNF and the competitiveness of WC within the sward (Frame and Newbould, 1986). In contrast, under grazing, a large proportion of N taken up by the sward is directly recycled in excreta of the grazing livestock. Animal treading and

selective grazing affects the WC content of grassland. Under grazing, transfer of fixed N from WC to grass can be higher and the competitive ability of WC is lower than under cutting. Hence, strategic harvesting of herbage for conservation as winter feed benefits the competitiveness and persistence of WC in swards.

Rotation length in rotational grazing systems

In the UK and Ireland, the recommended grazing rotation lengths are approximately 21 days in late spring and summer and increase to approximately 35 days in autumn. One of the advantages of WC is the lower rate of decline of nutritive value with increasing maturity compared with PRG. Digestibility and voluntary DM intake of grasses decreased with each week of increased rotation interval by approximately 20 g/kg and 0.2 kg/day, respectively, while the rate of decline of WC herbage was half that of PRG (Peyraud *et al.*, 2009). This can make WC-based pastures easier to manage than grass-only pastures; rotation lengths can be longer without adverse effects on the nutritive value of the sward, particularly during the late summer and autumn when the PRG component of the sward remains largely in the vegetative state (much less likely to produce flower and seed heads).

Rotation lengths are often extended in autumn to increase the mass of herbage available on the farm. By this means, grazing can be extended into the late autumn and early winter. Phelan *et al.* (2014) studied late summer and autumn grazing, examining the impact of rotation lengths between 21 days and 84 days on herbage production, WC persistence and carry-over effects into the following spring and early summer. A 42-day rotation length during the late summer and autumn gave optimum herbage production, nutritive value, WC content and stolon mass, and enabled greater management flexibility in extending the grazing season into the late autumn and early winter.

Autumn and winter management

WC can be the dominant component of pasture during the late summer and autumn. Sward WC content typically declines in winter. Its leaves tend to be positioned lower in the sward than grass leaves. As a result WC is less competitive with grasses for light during the winter and early spring. Hence, sward management in late autumn, winter and early spring is critical for the persistency of WC in grassland. A prolonged period without defoliation during the winter has a pronounced negative effect on WC content of swards (Laidlaw and Stewart, 1987; Laidlaw *et al.*, 1992). In contrast, grazing during the winter increased BNF and herbage DM production during the following growing season by 35% and 10%, respectively (Phelan *et al.*, 2013b).

The WC content of swards and bloat

Grassland with very high WC content is sometimes associated with bloat. Bloat is mainly a problem when there is a sudden introduction of WC into the

diet of grazing ruminants, for example where livestock are moved from WC-free to WC-rich swards. The incidence of bloat is negligible where the rumen flora of grazing livestock has become adapted to a WC-rich diet where the WC content of the sward increases steadily over the course of a growing season.

The WC content of swards, sward renovation and over-seeding

In grass–arable rotations, the relatively high WC content of swards is maintained when leys are laid down for periods of less than 5 years. In permanent grassland, WC is often not as persistent as the accompanying PRG. As an insurance against WC die-out in permanent grassland, Humphreys *et al.* (2008, 2009) demonstrated in a full-scale production system spanning 11 years that WC can be established and maintained by over-seeding into grass silage stubble. The WC content can be maintained by a programme of over-seeding of about one-fifth of the permanent grassland area each year, securing consistent contribution of WC from year to year.

Conclusions – management

An important obstacle to the wider adoption of WC in permanent pastures is inconsistent production within and between years associated with variable WC persistence, herbage production and BNE. Management practices to promote the persistency of WC in permanent pastures include low N fertilization, reseeded or over-sowing at least one-fifth of the grassland area each year and alternate harvesting for silage within and between years. In temporary grass–WC leys, persistency of WC is not as big a problem but can still be improved by breaks of over 2 years between grass–WC leys. Low post-grazing height should be used (4 cm under rotational grazing), particularly during the winter and spring. A long grazing season can be achieved by applying mineral N to swards in the late winter and early spring and increasing rotation lengths to 42 days in the autumn under rotational grazing. Bloat is generally not an important impediment when livestock are conditioned to grazing WC-rich grassland throughout the growing season.

Economics

It was pointed out above that the substantial increases in the cost of fertilizer N increase the economic performance of WC-based systems compared with grass only. Humphreys *et al.* (2012) showed that dairy production based on N-fertilized grassland was consistently more profitable than WC-based production between 1990 and 2005, which is in general agreement with many previous studies in the north-west of Europe. However, with the steady increase in fertilizer N prices relative to milk price, the difference between N-fertilized and WC-based systems was less clear cut between 2006 and 2010. Projecting into the future and assuming similar trends in fertilizer N and milk prices to the previous decade, this study indicated

that WC will become an increasingly more profitable alternative to fertilizer N for pasture-based dairy production.

Environmental Impact

The manufacture of synthetic fertilizer N accounts for 2% of global fossil energy use. There is a strong link between energy prices and fertilizer prices. For environmental as well as economic reasons, the challenge for pasture-based farming systems is to become more N efficient and less reliant on synthetic fertilizers. Energy efficiency, calculated as herbage unit of feed for lactation (UFL) produced per 1 MJ of energy consumed is three times higher for WC–grass pastures than for fertilized grass pastures (2.5 UFL/MJ versus 0.8 UFL/MJ; Besnard *et al.*, 2006).

Losses of N to water

Dairy production systems in Europe are to a large extent based on ley–arable rotations (Vertés *et al.*, 2007). As a consequence of the soil N build-up, the ploughing of grass–WC mixtures is followed by a rapid and extended period of N mineralization as a source of nitrate for leaching. This release of nitrate is often substantial in the first year after cultivation, with N fertilizer replacement values often exceeding 100 kg/ha (Eriksen *et al.*, 2008) and relatively little variation in this value due to grassland age or management, even where there are large differences in grassland fertilization (Eriksen, 2001; Hansen *et al.*, 2005). Mineralization of N following grassland cultivation is a two-stage process with a rapid mineralization over the first 160–230 days, followed by a second phase with mineralization rates two to seven times lower than in the first phase (Vertés *et al.*, 2007). Intense rotary cultivation of the grass sward prior to ploughing can cause quicker availability and better synchrony between N mineralization and plant uptake (Eriksen and Jensen, 2001). The release of large quantities of N from the grass–WC residues means that fertilizer N input to subsequent cereals can be reduced or even eliminated in the first following crop. Catch crops are useful during winters in the arable phase of the crop rotation to reduce nitrate leaching, by removing soil mineral N from the soil profile before winter drainage starts (Hansen *et al.*, 2007).

The general consensus is that the size of N losses to water from permanent pasture-based systems (as nitrate, ammonium, organic N) under a particular set of circumstances of soil, climate and system management depends largely on the amount of N circulating within the system. It is also widely accepted that it does not matter whether the initial source of N is synthetic fertilizer N or from BNF (Ledgard *et al.*, 2009).

Ammonia

Ammonia gas emission from agricultural sources and subsequent re-deposition contributes to the eutrophication and acidification of water bodies and to indirect

nitrous oxide emissions. A recent N balance study carried out under the Legume Futures project found that ammonia gas was the largest pathway for environmentally damaging N loss from a WC-based system in Ireland (Burchill *et al.*, 2016). The main sources of ammonia losses on grazed pasture-based farms are from urine patches in grazed swards, fertilizer N applications (i.e. urea), livestock winter housing and the storage, agitation and field application of manures. At the farm scale, as with N losses to water, the intensity of urine patches or slurry application to fields typically depends on the farm stocking density; the more N that is circulating within the system, the greater the extent of ammonia losses. Another source of ammonium for volatilization to ammonia is fertilizer N, particularly ammonium-based fertilizers and urea. Although this issue has not been investigated to any great extent, Ledgard *et al.* (2009) expressed the opinion that the pulse of N in soil following the application of fertilizer N results in greater risk of ammonia loss than the steady release from mineralization of N from WC residues in soil. From this perspective, it seems probable that WC-based grassland carries less risk of ammonia losses than grassland receiving synthetic fertilizer N when all other conditions, such as stocking density, are common to both systems.

Greenhouse gases (GHGs)

Nitrous oxide is a potent GHG with a global warming potential 298 times higher than carbon dioxide over a 100-year time horizon (Solomon *et al.*, 2007). In addition, nitrous oxide currently is the single most important stratospheric ozone-depleting substance and is expected to remain the largest throughout the 21st century (Ravishankara *et al.*, 2009). WC has the potential to impact on nitrous oxide emissions from grassland due to its influence on soil N availability. As with N losses to water and ammonia emissions, at comparable levels of production indirect nitrous emissions resulting from N recycled in livestock excreta are similar for both WC-based and grass pasture. Nevertheless Li *et al.* (2011) found a trend for lower direct and indirect emissions from grazed WC than from N-fertilized grassland. Emissions were 16–19% lower from the WC-rich swards although the stocking density of dairy cows was similar. The lower emissions can be explained by the lower input of N fertilizer, by the process of BNF being a negligible source of nitrous oxide, and by the greater efficiency of WC-rich swards in transforming N into biomass. Following a comprehensive review of the topic, Rochette and Janzen (2005) suggested that evidence for direct release of nitrous oxide from BNF was inadequate to justify a nitrous oxide emission factor for BNF similar to that of fertilizer N.

Carbon footprint calculated by life cycle assessment (LCA) was used to compare GHG emissions from pasture-based milk production based on WC-rich or N-fertilized swards (Yan *et al.*, 2013). Emissions of both nitrous oxide and carbon dioxide were lower in WC, whereas emissions of methane (per kilogram of energy corrected milk) were similar in both systems. Replacing fertilizer N by BNF was shown to have the potential to lower the carbon footprint of pasture-based milk production.

Conclusions – environmental impact

From an environmental perspective, the main advantage of WC-based systems stems from the replacement/reduction of fertilizer N by BNF with all the effects associated with the reduced production of fertilizer. There is generally less N circulating within lower stocked WC-based systems resulting in lower N losses to water and lower ammonia and methane emissions to the atmosphere; losses that are often closely related to stocking density. In addition, direct emissions of nitrous oxide are lower from WC-rich grassland compared with N-fertilized grassland at the same level of productivity and substantially lower than intensively fertilized grassland. Using LCA, a number of studies have shown that WC-based systems have between 11% and 26% lower carbon footprint per litre of milk compared with N fertilized systems, the biggest differences being with more intensive systems reliant on high input of fertilizer N.

Conclusions

WC generally does not make a significant contribution to forage production on conventional farms in Western Europe, but there is considerable potential for growth due to rising fertilizer N costs and implementation of environmental regulations curtailing fertilizer N use and stocking densities on farms. With rising energy and fertilizer N costs, it is likely that WC will become an increasingly profitable alternative to intensively fertilized grass for pasture-based livestock systems in the future. The economic competitiveness is due to lower costs of production that compensate for the lower productivity of WC-based systems. Lower productivity, lower stocking densities and less N circulating within the system contribute to lower losses of N to water and ammonia and GHGs to the atmosphere. WC has the additional advantage of lower direct emissions of nitrous oxide (an important GHG) at the same level of productivity and substantially lower direct and indirect emissions compared with intensively fertilized grassland. From the perspective of the overall future sustainability of pasture-based ruminant production, WC-based systems offer economic competitiveness, lower energy dependency and lower environmental impact.

References

- Aaes, O. and Kristensen, E.S. (1994) Effect of N-fertilisation, stocking rate and supplement type and amount at grazing in regulated continuous systems. *Statens Husdyrbrugsforsøg, Intern Rapport 27*, 49–59.
- Andrews, M., Scholefield, D., Abberton, M.T., McKenzie, B.A., Hodge, S. and Raven, J.A. (2007) Use of white clover as an alternative to nitrogen fertilizer for dairy pastures in nitrate vulnerable zones in the UK: productivity, environmental impact and economic considerations. *Annals of Applied Biology* 151, 11–23.
- Besnard, A., Montarges-Lellahi, A. and Hardy, A. (2006) Systèmes de culture et nutrition azotée. Effets sur les émissions de GES et le bilan énergétique. *Fourrages* 187, 311–320.

- Bryant, A.M., MacDonald, K.A. and Clayton, D.G. (1982) Effects of nitrogen fertilizer on production of milk solids from grazed pasture. *Proceedings of the New Zealand Grassland Association* 43, 58–63.
- Burchill, W., James, E.K., Li, D., Lanigan, G., Williams, M., Iannetta, P.P.M. and Humphreys, J. (2014) Comparisons of biological nitrogen fixation in association with white clover (*Trifolium repens* L.) under four fertiliser nitrogen inputs as measured using two ¹⁵N techniques. *Plant and Soil* 385, 287–302.
- Burchill, W., Lanigan, G., Li, D., Williams, M. and Humphreys, J. (2016) A system N balance for a pasture-based system of dairy production under moist maritime climatic conditions. *Agriculture, Ecosystems and Environment* 220, 202–210.
- Davies, A. (2001) Competition between grasses and legumes in established pastures. In: Tow, P.G. and Lazenby, A. (eds.) *Competition and Succession in Pastures*. CAB International, Wallingford, UK, pp. 63–83.
- Enriquez-Hidalgo, D., Gilliland, T., Deighton, M., O'Donovan, H.M. and Hennessy, D. (2014) Milk production and enteric methane emissions by dairy cows grazing fertilized perennial ryegrass pasture with or without inclusion of white clover. *Journal of Dairy Science* 97, 1400–1412.
- Eriksen, J. (2001) Nitrate leaching and growth of cereal crops following cultivation of contrasting temporary grasslands. *Journal of Agricultural Science* 136, 271–281.
- Eriksen, J. and Jensen, L.S. (2001) Soil respiration, nitrogen mineralisation and uptake in barley following cultivation of grazed grasslands. *Biology and Fertility of Soils* 33, 139–145.
- Eriksen, J., Askegaard, M. and Søegaard, K. (2008) Residual effect and nitrate leaching in grass–arable rotations: effect of grassland proportion, sward type and fertilizer history. *Soil Use and Management* 24, 373–382.
- European Council (1991) Directive 91/676/EEC concerning the protection of waters against pollution caused by nitrates from agricultural sources. *Official Journal of the European Union* L375, 1–8.
- European Parliament and Council (2000) Directive 2000/60/EC establishing a framework for community action in the field of water policy. *Official Journal of the European Union* L327, 1–73.
- European Parliament and Council (2001) Directive 2001/81/EC on national emission ceilings for certain atmospheric pollutants. *Official Journal of the European Union* L309, 22–30.
- Eurostat (2013) Eurostat. European Commission, Brussels. Available at: <http://ec.europa.eu/eurostat> (accessed 18 March 2013).
- Frame, J. and Boyd, A.G. (1987) The effect of strategic use of fertilizer nitrogen in spring and/or autumn on the productivity of a perennial ryegrass/white clover sward. *Grass and Forage Science* 42, 429–438.
- Frame, J. and Newbould, P. (1986) Agronomy of white clover. *Advances in Agronomy* 40, 1–88.
- Gibb, M.J., Huckle, C.A., Nuthall, R. and Rook, A.J. (1997) Effect of sward surface height on intake and grazing behaviour by lactating Holstein Friesian cows. *Grass and Forage Science* 52, 309–321.
- Hansen, J.P., Eriksen, J. and Jensen, L.S. (2005) Residual nitrogen effect of a dairy crop rotation as influenced by grass–clover ley management, manure type and age. *Soil Use and Management* 21, 278–286.
- Hansen, E.M., Eriksen, J. and Vinther, F.P. (2007) Catch crop strategy and nitrate leaching following a grazed grass–clover. *Soil Use and Management* 23, 348–358.
- Harris, W. (1987) Population dynamics and competition. In: Baker, M.J. and Williams, W.M. (eds) *White Clover*. CAB International, Wallingford, UK, pp. 203–298.
- Hay, M.J.M., Brock, J.L. and Thomas, V.J. (1989) Density of *Trifolium repens* plants in mixed swards under intensive grazing by sheep. *Journal of Agricultural Research* 113, 81–86.
- Humphreys, J., O'Connell, K. and Casey, I.A. (2008) Nitrogen flows and balances in four grassland-based systems of dairy production on a clay-loam soil in a moist maritime climate. *Grass and Forage Science* 63, 467–480.

- Humphreys, J., Casey, I.A. and Laidlaw, A.S. (2009) Comparison of milk production from clover based and fertilizer N based grassland on a clay-loam soil under moist temperate climatic conditions. *Irish Journal of Agricultural and Food Research* 48, 189–207.
- Humphreys, J., Mihailescu, E. and Casey, I.A. (2012) An economic comparison of systems of dairy production based on N fertilised grass and grass–white clover grassland in a moist maritime environment. *Grass and Forage Science* 67, 519–525.
- Keogh, B., Humphreys, J., Phelan, P., Necpalova, M., Casey, I.A. and Fitzgerald, E. (2010) The effect of organic management strategies on dairy production in clover-based grassland. *Grassland Science in Europe* 15, 958–960.
- Laidlaw, A.S. (1980) The effect of fertilizer nitrogen applied in swards of ryegrass sown with four cultivars of white clover. *Grass and Forage Science* 35, 295–299.
- Laidlaw, A.S. and Stewart, T.A. (1987) Clover development in the sixth to ninth year of a grass/clover sward as affected by out-of-season management and spring fertilizer nitrogen application. *Research and Development in Agriculture* 4, 155–160.
- Laidlaw, A.S., Teuber, N.G. and Withers, J.A. (1992) Out-of-season management of grass/clover swards to manipulate clover content. *Grass and Forage Science* 47, 220–229.
- Leach, K.A., Bax, J.A., Roberts, D.J. and Thomas, C. (2000) The establishment and performance of a dairy system based on perennial ryegrass: white clover swards compared with a system based on nitrogen fertilised grass. *Biological Agriculture and Horticulture* 17, 207–227.
- Ledgard, S.F., Crush, J.R. and Penno, J.W. (1998) Environmental impacts of different nitrogen inputs on dairy farms and implications for the Resource Management Act of New Zealand. *Environmental Pollution* 102, 515–519.
- Ledgard, S.F., Penno, J.W. and Sprosen, M.S. (1999) Nitrogen inputs and losses from clover/grass pastures grazed by dairy cows, as affected by nitrogen fertilizer application. *Journal of Agricultural Science* 132, 215–225.
- Ledgard, S.F., Sprosen, M.S., Penno, J.W. and Rajendram, G.S. (2001) Nitrogen fixation by white clover in pastures grazed by dairy cows: temporal variation and effects of nitrogen fertilisation. *Plant and Soil* 299, 177–187.
- Ledgard, S.F., Schils, R.L.M., Eriksen, J. and Luo, J. (2009) Environmental impacts of grazed clover/grass pastures. *Irish Journal of Agricultural and Food Research* 48, 209–226.
- Li, D., Lanigan, G. and Humphreys, J. (2011) Measured and simulated nitrous oxide emissions from ryegrass- and ryegrass/white clover-based grasslands in a moist temperate climate. *PLoS One* 6, e26176.
- Peyraud, J.L., Le Gall, A. and Lüscher, A. (2009) Potential food production from forage legume-based systems in Europe: an overview. *Irish Journal of Agricultural and Food Research* 48, 1–22.
- Phelan, P. (2013) Aspects of grazing management to improve the productivity and persistence of white clover in Irish grassland. PhD thesis, Waterford Institute of Technology, Waterford, Ireland.
- Phelan, P., Casey, I.A. and Humphreys, J. (2013a) The effect of target post-grazing height treatment on herbage yields and dairy production from grass–white clover swards. *Journal of Dairy Science* 96, 1598–1611.
- Phelan, P., Keogh, B., Casey, I.A., Necpalova, M. and Humphreys, J. (2013b) The effects of treading by dairy cows on soil properties and herbage production in white clover based grazing systems on a clay loam soil. *Grass and Forage Science* 6, 548–563.
- Phelan, P., Casey, I.A. and Humphreys, J. (2014) The effects of simulated summer-to-winter grazing management on herbage production in a grass–clover sward. *Grass and Forage Science* 69, 251–265.
- Ravishankara, A.R., Daniel, J.S. and Portmann, R.W. (2009) Nitrous oxide (N₂O): the dominant ozone-depleting substance emitted in the 21st century. *Science* 326, 123–125.

- Rochette, P. and Janzen, H.H. (2005) Towards a revised coefficient for estimating N₂O emissions from legumes. *Nutrient Cycling in Agroecosystems* 73, 171–179.
- Ryan, M. (1986) Investigation of white clover for dairying. *Irish Grassland Animal Production Association Journal* 20, 83–86.
- Ryan, M. (1989) Development of a legume-based dairy system. In: Plancquaert, P. and Haggar, R. (eds) *Legumes in Farming Systems*. European Economic Community (EEC), Brussels, pp. 159–167.
- Schils, R.L.M., Boxem, T.J., Sikkema, K. and André, G. (2000a) The performance of a white clover based dairy system in comparison with a grass/fertilizer-N system. I. Botanical composition and sward utilization. *Netherlands Journal of Agricultural Science* 48, 291–303.
- Schils, R.L.M., Boxem, T.J., Jagtenberg, C.J. and Verboon, M.C. (2000b) The performance of a white clover based dairy system in comparison with a grass/fertilizer-N system. II. Animal production, economics and environment. *Netherlands Journal of Agricultural Science* 48, 305–318.
- Søegaard, K., Lund, P., Vinther, F., Petersen, S.O. and Aaes, O. (2001) Grazing with dairy cows. Effects of white clover, PBV- and AAT-level in supplement, cutting/grazing, ammonia volatilization and N₂-fixation on yield and N-balances. DJF-report 51, 103 pp. (In Danish.)
- Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K., Tignor, M., Miller, H.L. and Zhenlin, C. (2007) *Climate change 2007: The physical science basis. Contribution of working group I to the fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC)*. Cambridge University Press, Cambridge.
- Steg, A., Van Straalen, W.M., Hindle, V.A., Wensink, W.A., Dooper, F.M.H. and Schils, R.L.M. (1994) Rumen degradation and intestinal digestion of grass and clover at two maturity levels during the season in dairy cows. *Grass and Forage Science* 49, 378–390.
- Trott, H., Wachendorf, M., Ingwersen, B. and Taube, F. (2004) Performance and environmental effects of forage production on sandy soils. I. Impact of defoliation system and nitrogen input on performance and N balance of grassland. *Grass and Forage Science* 59, 41–55.
- Vertés, F., Hatch, D., Velthof, G., Taube, F., Laurent, F., Loiseau, P. and Recous, S. (2007) Short-term and cumulative effects of grassland cultivation on nitrogen and carbon cycling in ley–arable rotations. *Grassland Science in Europe* 12, 227–246.
- Weissbach, F. and Ernst, P. (1994) Nutrient budgets and farm management to reduce nutrient emissions. In: 't Mannetje, L. and Frame, J. (ed.) *Proceedings of the 15th General Meeting of the European Grassland Federation*. European Grassland Federation, Wageningen, the Netherlands, pp. 343–360.
- Yan, M.J., Humphreys, J. and Holden, M.N. (2013) The carbon footprint of pasture-based milk production: can white clover make a difference? *Journal of Dairy Science* 96, 857–865.

10 Red Clover in Cropping Systems

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Abstract

Red clover has played an important role as a supplier of reactive nitrogen to cropping systems in European agriculture for hundreds of years. Today, it is mostly valued for its good nutritional properties for ruminants, and for reducing the need for nitrogen fertilizer inputs. Red clover is a short-lived perennial capable of producing dry matter yields in the range of 9–18 t/ha/year, but the yield declines sharply after the first 2 harvest years. It forms an efficient symbiosis with *rhizobium* and can fix in excess of 350 kg/ha of nitrogen, most of which is transferred to the harvested biomass. Red clover is rich in protein and minerals, and contains unique compounds that improve nitrogen use efficiency at farm level and that improve the quality of animal products for human consumption with respect to fatty acid profiles, compared with white clover or lucerne (alfalfa). Red clover is usually grown mixed with grasses. It should be sown in the first half of the growing season and is easy to establish. It thrives in most soils but does not tolerate very acid or wet soils. Systematic breeding has been carried out for more than 100 years, and the main focus of breeding programmes is to increase crop persistence through improved disease resistance and winter hardiness.

Introduction

Worldwide, red clover (*Trifolium pratense* L.) is the second most important sown forage legume after lucerne (alfalfa; *Medicago sativa* L.) in terms of seed sales and in the number of cultivars available (Boller *et al.*, 2010). As indicated by seed sales (Table 10.1), it is an important component of short-term leys, particularly in northern and Eastern Europe and North America. Red clover is indigenous to Europe, the Near East, North Africa and central Asia (Boller *et al.*, 2010), and has a long history of cultivation in Europe. It was domesticated and cultivated in

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Table 10.1. Certified red clover seed sales in Europe in 2010. (Data from European Seed Certification Agencies Association, 2014.)

Country	Quantities (t)	Country	Quantities (t)
Austria	74	Lithuania	0
Belgium	4	Luxembourg	0
Croatia	7	The Netherlands	0
Czech Republic	456	Poland	0
Denmark	349	Romania	6
Estonia	66	Serbia	67
Finland	49	Slovakia	13
France	2,342	Spain	7
Germany	797	Sweden	388
Hungary	20	Switzerland	60
Italy	199	UK	3
Latvia	60		

southern Spain in the 3rd and 4th centuries. By the middle of the 16th century red clover was grown in the Netherlands and by the 17th century across most of Europe (Kjærgaard, 1995). The species played an important role in transforming the increasingly unsustainable production systems that prevailed in Europe in the 16th and 17th centuries and provided the basis for a substantial increase in agricultural production as it became part of new cropping systems (Kjærgaard, 1995). The major system change was the extension of the crop rotation from a 3- to a 4-year system, and the replacement of the fallow year with the cultivation of red clover, which improved soil fertility. As a result of this system change, wheat yields in Europe more than doubled (Grigg, 1992).

Red clover is a diploid and out-crossing species that is pollinated by bumblebees (*Bombus* spp.) and honeybees (*Apis mellifera* L.). The ease of establishment, high seedling vigour, rapid growth, high forage quality and excellent soil improvement characteristics are important advantages. It is a temperate crop adapted to a wide range of soil and environmental conditions (Frame *et al.*, 1998). Another important feature of red clover is the reduced rate of decline in digestibility with advancing maturity in comparison with grasses. Thus, mixing red clover with grasses increases the time span within which a highly digestible crop suitable for feeding high-yielding dairy cows can be harvested (Rinne and Nykänen, 2000; Dewhurst *et al.*, 2009).

Red clover is most commonly used as silage for winter feeding of ruminants. It can be included in grazed swards, but this will decrease its production potential (Frankow-Lindberg, 1985) and it is not as well suited to grazing as white clover. In addition to forage use, red clover can be cultivated for green manuring. It can either be sown on its own when the nitrogen fertilization effect is utilized by the non-N₂ fixing plant growing after clover, or undersown in a non-N₂ fixing plant. Globally, the use of red clover has decreased since the 1950s due to the access to cheap nitrogen fertilizers, but increasing prices of these and a stronger emphasis on home-grown protein in recent years have rekindled interest in this legume.

Botany

Morphology

Red clover is a short-lived perennial species with peak production during the 2–3 first harvest years (Frame *et al.*, 1998). It has an upright growth habit that makes it most useful for mowing. The plant forms a rosette, and the regrowth after the first cut is produced from axillary buds formed at the base of the plant. It has a deep taproot and is moderately tolerant of drought conditions.

Red clover is a quantitative long-day species, but the response differs between populations. There are early, medium and late types depending on its flowering response to the day length. Early red clover types (i.e. those least responsive to day length) produce more than one generation of axillary buds, so can withstand several cuts per year. Late types (i.e. those most responsive to day length) produce only one new generation of axillary buds per year, so can tolerate only one cut per year. The early types are suitable for southern latitudes and the later for northern latitudes. In North America, the types are termed medium or double-cut, and mammoth or single-cut types, respectively (Boller *et al.*, 2010).

Plant breeding

In 1742, Carl von Linné noted in Sweden that ‘Spanish clover, which is the same species as our native red clover, is bigger in size, but not very persistent. Further, it does not reseed itself as our native species does’ (Osvald, 1962). Selection among native plant material for persistent and productive material therefore formed the basis for the breeding of well-adapted red clover cultivars (Boller *et al.*, 2010). Before red clover was the subject of targeted breeding, locally adapted populations, termed landraces, were developed by harvesting and re-sowing seed within a restricted area (Boller *et al.*, 2010). Swiss landraces are genetically distinct from Swiss natural populations (Hermann *et al.*, 2005), which indicates that the cultivated landraces were valued by farmers and that care was taken to maintain their traits.

Breeding based on landraces began as early as 1910 in Sweden (Sjödin, 1986). The most important characteristics bred for then related to resistance to nematodes and *Sclerotinia trifoliorum*. These traits as well as general persistence and winter hardiness continued to be the focus of efforts (Sjödin, 1986), not just in Sweden, but globally (Boller *et al.*, 2010). Systematic red clover breeding in other parts of the world began after World War II (Boller *et al.*, 2010), and in many countries more persistent and disease-resistant cultivars were produced compared to the landraces. The most widely used breeding methods are recurrent mass selection and maternal line selection (Boller *et al.*, 2010).

The development of tetraploid cultivars began in the 1940s. A common way to produce these is by colchicine treatment of young seedlings (Boller *et al.*, 2010) which then are used for intercrossing. Tetraploid plants are larger than diploids, with improved disease resistance and persistence, but seed production has proved to be a challenge (Sjödin, 1986; Boller *et al.*, 2010).

Currently, there are 267 cultivars of red clover on the Organisation for Economic Co-operation and Development (OECD) list of cultivars eligible for seed certification (OECD, 2013). Seed production in Europe occurs mainly in France and Germany, but can be carried out as far north as central Sweden. Since red clover is an out-crossing species, genetic drift may occur within a short time span in environmentally challenging environments (Collins *et al.*, 2012). This means that care is needed to retain the properties of a cultivar over time when it is multiplied.

Agronomy

Seed mixtures

Red clover is sown mostly in mixtures with grasses as companion species. This practice increases total yield and protects against weeds and plant diseases (Frankow-Lindberg *et al.*, 2009a). In addition, the risk of nitrogen leaching from mixed grass–clover swards is less than in pure red clover (Frankow-Lindberg and Dahlin, 2013). The recommended proportion of red clover seed in the seeding mixture varies depending on the main production objective of the crop. Where maximum protein yield is the objective, the stand should be dominated by clover. To achieve this, 12–15 kg/ha red clover seed and 4–5 kg/ha grass seed (Frame *et al.*, 1998) is recommended. In Sweden and Finland, the recommendation for a more general-purpose mixture has for a long time been 5–7 kg/ha red clover seed sown with 15 kg/ha grass seed (Frankow-Lindberg, 1990). The regulation of red clover content in such a mixed crop by varying seeding rates is rather limited once the rate exceeds 6 kg/ha. It depends to a much greater extent on management factors such as nitrogen application and harvesting regime (Frankow-Lindberg, 1989). Lower rates of red clover seed (and a higher rate of grass seed) are now common where the application of quite high rates of nitrogen fertilizer has become standard practice. To improve and stabilize the legume content (Frankow-Lindberg *et al.*, 2009b), and thereby the longevity of the crop, commercial seeding mixtures in Sweden now often contain both red and white clover seeds.

An important aspect of mixed swards is the contribution of biologically fixed nitrogen, which decreases the fertilizer nitrogen needed to achieve a specified dry matter yield (Nyfeler *et al.*, 2009). This is evident from the poor response to nitrogen application in red clover-dominated swards (Fig. 10.1). However, since it is a short-lived species, red clover content declines with time irrespective of initial seeding and nitrogen application rates (Frankow-Lindberg, 1989). In practical farming, the amount of nitrogen applied is therefore usually increased with time as the content of red clover in the crop decreases. The response of a clover–grass mixed sward to nitrogen fertilizer is strongest in the spring harvest. A recent field study of mixtures of grass and red or white clover showed that there was virtually no effect of applying nitrogen to the regrowth (Frankow-Lindberg unpublished results, Fig. 10.2). Unfortunately, it is very difficult to properly estimate the clover content in early spring when it is time for nitrogen application, and thus adjust rates to the actual content.

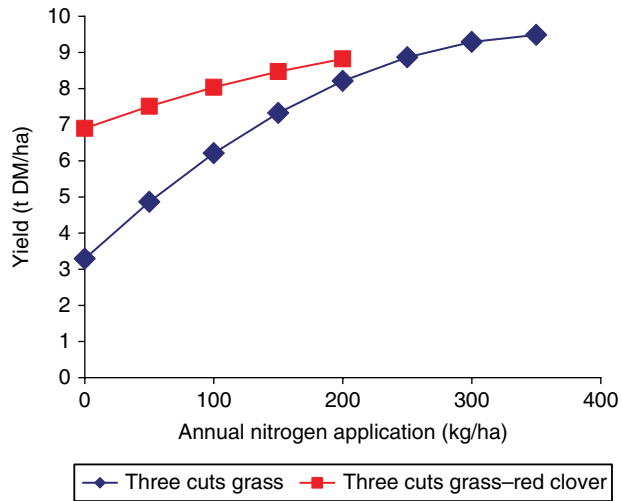


Fig. 10.1. The effect of nitrogen application on the dry matter (DM) yield of a mixed grass-red clover sward and a pure grass sward harvested three times. (Data from Kornher, 1982.)

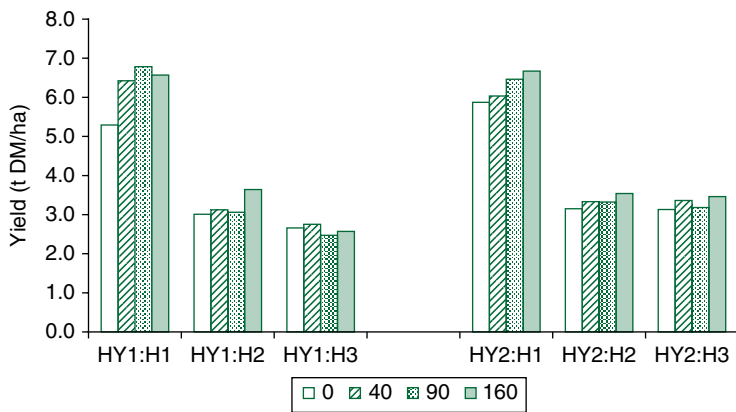


Fig. 10.2. The effect of nitrogen application on the dry matter (DM) yield of a mixed grass-red and white clover sward harvested three times. The treatments were: no nitrogen applied (0), 40 kg/ha nitrogen applied in spring (40), 90 kg/ha nitrogen applied in spring (90) and 90 kg/ha nitrogen applied in spring followed by 35 kg/ha nitrogen applied to each regrowth (160). HY1 and HY2 denote the first and the second harvest years, respectively. H1, H2 and H3 denote the respective harvests within each harvest year. The experiment was established 1 year before harvests began.

Timothy (*Phleum pratense* L.) is the traditional companion species due to its relatively low competitive ability. In the most northern regions where red clover is cultivated, this is the only grass species that is suitable. In southern Sweden, meadow fescue (*Festuca pratensis* Huds.) is often included, as well as small amounts of perennial ryegrass (*Lolium perenne* L.) and hybrid ryegrasses. In the UK, the recommended companion grasses are Italian ryegrass (*Lolium multiflorum* L.) or hybrid

ryegrasses. Other species used in the USA are cocksfoot (*Dactylis glomerata* L.), tall fescue (*Festuca arundinacea* Schreb.), smooth brome grass (*Bromus inermis* Leyss.) and reed canary grass (*Phalaris arundinacea* L.) in bi-species mixtures.

Red clover should be sown from early to mid-season at a depth of 10–15 mm in order to establish well before the winter (Frame *et al.*, 1998). Undersowing in a grain or silage (whole-crop) cereal nurse crop reduces weed pressure. Provided the cereal is harvested early and the straw removed, this practice does not impair the yield of the established ley crop. However, with such undersowing, a harvest in the establishment year is not possible. Slot-seeding into an existing sward can be successful, but competition from the existing swards must be controlled along the slots (Komárek *et al.*, 2010). Red clover does not thrive in very wet or acid soils, but is otherwise not demanding in relation to soil conditions. Ideally, soil pH should be in the range 6.0–6.5 for optimum crop development and root nodule formation (Frame *et al.*, 1998). With a dry matter yield of 10 t/ha (pure clover crop), uptake of phosphorus and potassium is approximately 30 kg/ha and 250 kg/ha respectively. This needs to be replenished. Regular fertilization with sulfur may also be required.

The number of cuts that may be taken per year, and the yields obtained, depend on climate. Where high-quality feed is required, three to four cuts are common in southern Sweden, and in countries further south up to five cuts per year can be taken. In northern Sweden and Finland the number of cuts varies from one to three depending on the latitude. Maximum dry matter yield (first harvest year, Europe) is in the range of 9–18 t/ha without nitrogen fertilizer (Frame, 2005). Yields decrease sharply after the second harvest year.

Fixation and Transfer of Nitrogen to Companion Species

Nitrogen acquisition through biological nitrogen fixation is high in red clover. Nitrogen fixation above 350 kg/ha/year in the above-ground biomass has been reported (Carlsson and Huss-Danell, 2003). An estimate of the total amount of biologically fixed nitrogen by red clover (above and below ground) is approximately 50 kg/t dry matter harvested when it is grown in mixtures with grasses (Frankow-Lindberg, 2003). Around 80% of the nitrogen in the stand comes from biological nitrogen fixation when red clover is grown in mixtures with grasses (Carlsson and Huss-Danell, 2003). The presence of grasses increases the quantity of nitrogen fixed by red clover by providing a sink for the nitrogen fixed, while high application rates of nitrogen fertilizer decrease this directly by suppressing the proportion of fixed nitrogen in the plant (Nyfeler *et al.*, 2011) and indirectly through reducing the proportion of clover in the sward (Nykänen *et al.*, 2008). Few studies have estimated the amounts of biologically fixed nitrogen present in the stubble and the root system. In one study from northern Sweden (with two harvests taken), between 25% and 60% of the total amount of nitrogen fixed was found below harvesting height, in the respective cuts (Huss-Danell *et al.*, 2007). It was concluded then that the fixed nitrogen found in non-harvested plant parts is 40% of the amounts found in the harvested plant material.

There is usually no need to inoculate red clover seeds with *rhizobium* at sowing since most European soils contain species that readily colonize and form an

efficient symbiosis with it (Frame *et al.*, 1998). Nitrogen fixed by red clover eventually becomes available to companion species, most likely through *in situ* decomposition of clover tissue deposited above and below ground (Dahlin and Stenberg, 2010a). The transfer of fixed nitrogen from red clover to a non-fixing species is less than from white clover (*Trifolium repens* L.) (Høgh-Jensen and Schjoerring, 2000) but more than in lucerne (*M. sativa* L.) (Pirhofer-Waltzl *et al.*, 2012; Frankow-Lindberg and Dahlin, 2013). The amount of nitrogen transferred increases over time, and transfers of up to 68 kg/ha have been recorded (Høgh-Jensen and Schjoerring, 2000; Dahlin and Stenberg, 2010b).

As red clover is a short-lived species, it is often grown in short-term leys in crop rotations where cereals are included, providing residual effects of the ley crop on the following crops. Lindén (2008), summarizing a large number of conventional farming field trials in Sweden, stated that the main residual effect of red clover-based leys is a nitrogen effect. The residual effect of these crops reduces the fertilizer nitrogen requirement of the following cereal crop by 30–40 kg/ha. The effect is largest in the cereal crops grown directly after the ley crop. This contributes to a yield benefit of 0.7–1.0 t/ha for winter wheat grain compared with yields after a barley pre-crop. This pre-crop effect is still noticeable in the second cereal crop with a benefit of 0.25–0.75 t/ha for winter wheat (Lindén, 2008). When red clover was intercropped (undersown) with winter wheat and ploughed in after the wheat harvest, it provided both weed control and nitrogen to the following barley crop without causing a yield penalty to the covering winter wheat crop (Bergkvist *et al.*, 2011) (Fig. 10.3).



Fig. 10.3. Red clover as a cover crop undersown in winter wheat. The yield of winter wheat was unaffected by the presence of red clover, while the yield of the following barley crop was increased by the ploughed-under red clover. (Photo credit: Göran Bergkvist.)

Feeding Quality

Red clover provides a high-quality fodder not only for ruminants (Dewhurst *et al.*, 2009), but also for pigs (Reverter *et al.*, 1999) and fish (Turan, 2006). Red clover is rich in protein and minerals, and intake rate by ruminants is high. This is due to its cell structure, which differs from grass in that it breaks down more easily in the rumen and thus passes through the rumen more rapidly (Dewhurst *et al.*, 2009). On average, the daily intake of dry matter from red clover-based diets are 1.2 kg higher than from grass diets, and the daily milk yield is increased by an average of 1.5 kg (Steinshamn, 2010). Further, in contrast to white clover, red clover contains the enzyme polyphenol oxidase (PPO), which provides the forage with beneficial properties such as reducing emissions of nitrogen to the environment (Parveen *et al.*, 2010) as well as improved milk and meat quality. PPO produces quinones that bind to proteins, which in turn reduces protein degradability during silage making. As a result, the feeding quality of the silage is improved, and nitrogen losses from the silage through effluents during storage are reduced. PPO also reduces the protein degradability in the rumen (Parveen *et al.*, 2010), which improves the nitrogen use efficiency of ruminants fed red clover compared with those fed with white clover (Dewhurst *et al.*, 2009). PPO is also thought to be involved in the reduction of rumen biohydrogenation of polyunsaturated fatty acids (Van Ranst *et al.*, 2011). This results in higher levels of the n-3 fatty acid α -linolenic acid in milk from dairy cows fed red clover silage than from cows fed grass-based diets (Dewhurst *et al.*, 2009). This has positive effects on consumer health. Meat from cattle consuming red clover-rich forage also has a more beneficial fatty acid profile with respect to consumer health than cattle consuming all-grass or white clover-rich forage (Dewhurst *et al.*, 2009). Another feature of milk from dairy cows fed on red clover is the high concentrations of the isoflavone equol, which may confer potential positive health effects for consumers similar to those observed in human populations where soy products are included in the diets, for example reduced rates of cardiovascular diseases (Tham *et al.*, 1998). A drawback of the presence of isoflavones (particularly formononetin) in red clover forage is their oestrogen-like effects within animals, because this is thought to impair the fertility of sheep (Dewhurst *et al.*, 2009). However, a recent study where diets fed to ewes consisted of either red clover or grass silage found no such effect (Mustonen *et al.*, 2014). Red clover contains more magnesium and calcium in relation to potassium compared with grasses, which is beneficial for the health of cows. The phosphorus concentration is low in relation to calcium, which has to be taken into consideration when the cows are in the late phase of pregnancy. Low phosphorus in cows' diets prior to calving can increase the incidence of postparturient hypocalcemia (milk fever).

Forage from red clover can be a part of pig diets. Increasing forage feeding has been found to reduce the apparent digestibility of the diet compared with a traditional cereal-based diet (Andersson and Lindberg, 1997). However, the apparent ileal digestibility of the crude protein is not impaired (Reverter *et al.*, 1999), which shows that red clover is a good protein source also for monogastric animals.

Conclusions

Red clover can successfully be grown across Europe in areas not characterized by drought. It is most suitable for the production of preserved winter feed for cattle from short-term leys. The aftermath may be grazed, but this will penalize total yield. The yield potential of pure stands or mixed stands with grass is high (and higher than that from white clover) without any nitrogen applications. The full exploitation of red clovers' nitrogen fixation in rotational leys would considerably reduce the carbon footprint from the production of forage. However, more reliable predictors of red clover performance in mixed swards are needed to induce non-organic farmers to omit or strongly reduce nitrogen fertilization to such swards.

The quality of the forage produced from red clover-based leys is excellent, provided that the harvest is made at early phenological stages and the crop is well preserved. Forage rich in red clover is suitable for feeding high-yielding dairy cows, and the presence of PPO in red clover additionally provides the milk with, for human consumption, better nutritional fat qualities compared with forage made from white clover or grass. At the moment, such quality differences are not acknowledged by the market.

Red clover grown in crop rotations reduces the need of nitrogen fertilizer in following cereal crops and increases their yields. It may be intercropped with a cereal without any yield penalties of the main crop. Such practice has the potential to provide much of the nitrogen fixed by red clover to the following crop, but weather and soil conditions may modify the efficiency of this transfer. The lack of cheap herbicides for weed control in cereals intercropped with red clover is one bottleneck for the uptake of this practice by non-organic farmers. Further, if mineral nitrogen fertilizer is applied to boost cereal yield, the growth of red clover will be uncertain and the money spent to purchase red clover could be lost.

References

- Andersson, C. and Lindberg, J.E. (1997) Forages in diets for growing pigs 2. Nutrient apparent digestibilities in barley-based diets including red-clover and perennial ryegrass meal. *Animal Science* 65, 493–500.
- Bergkvist, G., Stenberg, M., Wetterlind, J., Båth, B. and Elfstrand, S. (2011) Clover cover crops under-sown in winter wheat increase yield of subsequent spring barley – effect of N dose and companion grass. *Field Crop Research* 120, 292–298.
- Boller, B., Schubiger, F.X. and Kölliker, R. (2010) Red clover. In: Boller, B., Posselt, U.K. and Veronesi, F. (eds) *Fodder Crops and Amenity Grasses*. Springer, New York, pp. 439–455.
- Carlsson, G. and Huss-Danell, K. (2003) Nitrogen fixation in perennial forage legumes in the field. *Plant and Soil* 253, 353–372.
- Collins, R.P., Helgadóttir, A., Frankow-Lindberg, B.E., Sköt, L., Jones, C. and Sköt, K.P. (2012) Temporal changes in population genetic diversity and structure in red and white clover grown in three contrasting environments in northern Europe. *Annals of Botany* 110, 1341–1350.
- Dahlin, A.S. and Stenberg, M. (2010a) Cutting regime affects the amount and allocation of symbiotically fixed N in green manure leys. *Plant and Soil* 331, 401–412.

- Dahlin, A.S. and Stenberg, M. (2010b) Transfer of N from red clover to perennial ryegrass in mixed stands under different cutting strategies. *European Journal of Agronomy* 33, 149–156.
- Dewhurst, R.J., Delaby, L., Moloney, A., Boland, T. and Lewis, E. (2009) Nutritive value of forage legumes used for grazing and silage. *Irish Journal of Agricultural and Food Research* 48, 167–187.
- European Seed Certification Agencies Association (2014) Available at: www.esca.org/index/action/page/id/9/title/certified-seed-quantities (accessed 2 February 2016).
- Frame, J. (2005) *Forage Legumes*. Food and Agriculture Organization of the United Nations (FAO), Rome, and Science Publishers, Inc., Enfield, New Hampshire, pp. 200–209.
- Frame, J., Charlton, J.F.L. and Laidlaw, A.S. (1998) *Temperate Forage Legumes*. CAB International, Wallingford, UK, pp. 181–224.
- Frankow-Lindberg, B.E. (1985) Betning och slätter av slåttervallens återväxt. Inverkan av intensiteten i utnyttjandet på vallens avkastning, kvalitet samt övervintringsförmåga. Sveriges lantbruksuniversitet, Institutionen för växtodling, Report 146, 19 pp. (In Swedish.)
- Frankow-Lindberg, B.E. (1989) The effect of nitrogen and clover proportion on yield of red clover–grass mixtures. Paper presented to XVI International Grassland Congress, Nice, France, 4–11 October 1989, pp. 173–174.
- Frankow-Lindberg, B.E. (1990) *Botanical Composition in Mixed Swards of Legumes and Grasses*. Review of literature as regards effects of different cultural practices in mixed swards of red clover, white clover or lucerne. Sveriges lantbruksuniversitet, Institutionen för växtodlingslära, Växtodling 17, 35 pp. (In Swedish with an English summary.)
- Frankow-Lindberg, B.E. (2003) Kvantifiering av kväve-fixering via baljväxter i fält – förslag till en ny modell i rådgivningsprogrammet STANK. Sveriges lantbruksuniversitet, Institutionen för ekologi och växtproduktionslära, Rapport 5, 24 pp. (In Swedish.)
- Frankow-Lindberg, B.E. and Dahlin, A.S. (2013) N₂ fixation, N transfer, and yield in grassland communities including a deep-rooted legume or non-legume species. *Plant and Soil* 370, 567–581.
- Frankow-Lindberg, B.E., Brophy, C., Collins, R.P. and Connolly, J. (2009a) Biodiversity effects on yield and unsown species invasion in a temperate forage ecosystem. *Annals of Botany* 103, 913–921.
- Frankow-Lindberg, B.E., Halling, M., Höglind, M. and Forkman, J. (2009b) Yield and stability of yield of single- and multi-clover grass–clover swards in two contrasting temperate environments. *Grass and Forage Science* 64, 236–245.
- Grigg, D. (1992) *The Transformation of Agriculture in the West*. Blackwell, Oxford, pp. 32–45.
- Hermann, D., Boller, B., Widmer, F. and Kölliker, R. (2005) Optimization of bulked AFLP analysis and its application for exploring diversity of natural and cultivated populations of red clover. *Genome* 48, 474–486.
- Høgh-Jensen, H. and Schjoerring, J.K. (2000) Below-ground nitrogen transfer between different grassland species: direct quantification by ¹⁵N leaf feeding compared with indirect dilution of soil ¹⁵N. *Plant and Soil* 227, 171–183.
- Huss-Danell, K. Chaia, E. and Carlsson, G. (2007) N₂ fixation and nitrogen allocation to above and below ground plant parts in red clover-grasslands. *Plant and Soil* 299, 215–226.
- Kjærgaard, T. (1995) Agricultural development and nitrogen supply from an historical point of view. *Biological Agriculture and Horticulture* 11, 3–14.
- Komárek, P., Pavlu, V. and Hejman, M. (2010) Effect of depth and width of cultivation and sowing date on the establishment of red clover (*Trifolium pratense* L.) by rotary slot-seeding into grassland. *Grass and Forage Science* 65, 154–158.
- Kornher, A. (1982) Vallskördens storlek och kvalitet. Inverkan av valltyp, skördetid och kvävegödsling. Swedish University of Agricultural Sciences, Grass and Forage Reports 1, 5–32. (In Swedish.)

- Lindén, B. (2008) Efterverkan av olika förfrukter: inverkan på stråsådesgrödors avkastning och kvävetillgång – en litteraturoversikt. Swedish University of Agricultural Sciences, Division of Precision Agriculture, Report 14, 65 pp. (In Swedish.)
- Mustonen, E., Taponen, S., Andersson, M., Sukura, A., Katila, T. and Taponen, J. (2014) Fertility and growth of nulliparous ewes after feeding red clover silage with high phyto-oestrogens concentrations. *Animal* 8, 1699–1705.
- Nyfelner, D., Huguenin-Elie, O., Suter, M., Frossard, E., Connolly, J. and Lüscher, A. (2009) Strong mixture effects among four species in fertilized agricultural grassland led to persistent and consistent transgressive overyielding. *Journal of Applied Ecology* 46, 683–691.
- Nyfelner, D., Huguenin-Elie, O., Suter, M., Frossard, E. and Lüscher, A. (2011) Grass–legume mixtures can yield more nitrogen than legume pure stands due to mutual stimulation of nitrogen uptake from symbiotic and non-symbiotic sources. *Agriculture, Ecosystems and Environment* 140, 155–163.
- Nykänen, A., Jauhiainen, L., Kemppainen, J. and Lindström, K. (2008) Field-scale spatial variation in yields and nitrogen fixation of clover–grass leys and in soil nutrients. *Agricultural and Food Science* 17, 376–393.
- Organisation for Economic Co-operation and Development (OECD) (2013) List of Varieties Eligible for Certification. Grasses and Legumes. Available at: <http://www.oecd.org/tad/standardsforseedtractorsforestfruitandvegetables/GrassesLegumeslistofvarietyseeds2013.pdf> (accessed 2 February 2016).
- Osvald, H. (1962) *Vallodling och växtföljder, uppkomst och utveckling i Sverige*. Natur och Kultur, Uppsala, Sweden, pp. 40. (In Swedish.)
- Parveen, I., Threadgill, M.D., Moorby, J.M. and Winters, A. (2010) Oxidative phenols in forage crops containing polyphenol oxidase enzymes. *Journal of Agricultural and Food Chemistry* 58, 1371–1382.
- Pirhofer-Walzl, K., Rasmussen, J., Høgh-Jensen, H., Eriksen, J., Søgaard, K. and Rasmussen, J. (2012) Nitrogen transfer from forage legumes to nine neighbouring plants in a multi-species grassland. *Plant and Soil* 350, 71–84.
- Reverter, M., Lundh, T. and Lindberg, J.E. (1999) Ileal amino acid digestibilities in pigs of barley-based diets with inclusion of lucerne, white clover, red clover or perennial ryegrass. *British Journal of Nutrition* 82, 139–147.
- Rinne, M. and Nykänen, A. (2000) Timing of primary growth harvest affects the yield and nutritive value of timothy–red clover mixtures. *Agricultural and Food Science* 9, 121–134.
- Sjödin, J. (1986) Foderväxter. In: *Svalöf 1886–1986. Växtförädling under 100 år*. Svalöf AB, Svalöv, Sweden, pp. 157–165. (In Swedish.)
- Steinshamn, H. (2010) Effect of forage legumes on feed intake, milk production and milk quality – a review. *Animal Science Papers and Reports* 28, 195–206.
- Tham, D.M., Gardner, C.D. and Haskell, W.L. (1998) Potential health benefits of dietary phytoestrogens: a review of the clinical, epidemiological, and mechanistic evidence. *The Journal of Clinical Endocrinology and Metabolism* 83, 2223–2235.
- Turan, F. (2006) Improvement of growth performance in tilapia (*Oreochromis aureus* L.) by supplementation of red clover (*Trifolium pratense*) in diets. *The Israeli Journal of Aquaculture-Bamidgeh* 58, 34–38.
- Van Ranst, G., Lee, M.R.F. and Fievez, V. (2011) Red clover polyphenol oxidase and lipid metabolism. *Animal* 5, 512–521.

11 Lucerne (Alfalfa) in European Cropping Systems

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Abstract

This chapter reviews knowledge on the agronomy, genetics, feeding value and harvesting methods used for lucerne (alfalfa; *Medicago sativa*), which is the temperate climate legume species with the highest protein yield. It has agronomic advantages (high forage production, adequate persistency and drought tolerance) and provides a high-quality feed for ruminants. Lucerne also has positive impacts on the environment such as soil structure, nitrogen fertility, carbon storage, and plant and animal biodiversity. Lucerne production supports sustainable farming systems. Besides seed production that generates significant economic activity, novel uses of lucerne for human or animal health or energy production are also being investigated. Proposals for measures to increase lucerne cultivation in European farming systems are provided.

Introduction

Lucerne (alfalfa; *Medicago sativa* L.) is a perennial herbaceous forage legume cultivated under a wide range of climatic conditions, from oases in North Africa to Siberia. The stems and leaves, which are rich in protein, are harvested several times a year. The combination of high-quality forage production and biological nitrogen fixation (BNF) addresses the dual challenge of food security and resource conservation. There is therefore renewed interest in the crop. Lucerne is favoured particularly for its beneficial effects on soil structure and fertility, nitrogen (N) and carbon (C) cycles, protection against erosion, pesticide and herbicide use, water

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quality and biodiversity. Lucerne cropping for seed production is an additional activity that ensures the availability of high-quality seed of adapted cultivars.

This chapter provides an overview of the origin of lucerne, its cultivation and use, and provides updated information on physiological, genetic and technical aspects related to its development, cropping and provision of ecosystem services.

Botany, Biology and Main Characteristics

Lucerne is phylogenetically close to clovers (*Trifolium* sp.), pea (*Pisum sativum* L.) and faba bean (*Vicia faba* L.). The seed is small (2 g/1000 seeds) and is sown at a high density (about 20 kg of seeds/ha). A seedling is formed by a primary root and primary axis. The first leaf is unifoliolate while the subsequent leaves are trifoliolate. The establishment of a lucerne stand is quite slow, but after 3 months, the plants form vigorous erect leafy stems that can reach 120 cm in height. After cutting, new stems are formed from the axillary buds of remaining stem sections and/or from the collar at the base of the plant. Over several cutting cycles, a large crown and a deep rooting system are established. The taproot explores deep layers of soil (potentially exceeding 2 m depth). The allocation of assimilates (sugars and proteins) to the root determines the stand persistency. Because of intense competition among plants for light and nutrients, the plant density decreases over time, especially during the first 6 months after sowing, to about 300 plants/m². Winter survival is mainly determined by the degree of autumn–winter dormancy, which is linked to responses to reducing day length that results in low growth activity.

Lucerne is an out-crossing species (i.e. it is allogamous). Various morphological characters limit self-pollination before flower tripping is carried out by pollinating insects. Self-pollination is not restricted by incompatibility genes but seeds mostly originate from cross-pollination. Self-fertilization leads to inbreeding depression, so heterozygosity predominates in all populations.

Area of Production, Yield, Harvest Methods and Use

Lucerne is grown in pure stands in Europe on nearly 2.5 million ha, of which over 65% are located in Italy, France, Romania and Spain (Table 11.1). About 140,000 ha in Spain, 90,000 ha in Italy and 80,000 ha in France are grown to produce lucerne for drying or high protein (17–22%) pellets. Estimates that consider legume–grass mixtures (usually excluded from country statistics) suggest that lucerne is the most widely grown forage legume in 15 countries of south, east or west Europe (along with red or white clover in a few cases).

The crops are mechanically harvested after the budding stage and the forage (stems and leaves) is stored as hay or silage or dried in factories (Fig. 11.1). Lucerne is adapted to infrequent mowing. Grazing is also used in some regions, particularly in extensive systems because of its low cost. Although stands can persist for up to 10 years, the crops are usually harvested over a 3–5 year period.

Annual forage yields usually range between 4 t/ha and 15 t/ha, with three to seven harvests per year at 5–8 week intervals. Fewer harvests, usually with lower

Table 11.1. Production of lucerne in Europe: cultivated area and cultivated area as a proportion of the utilized agricultural area (UAA). The most widely used forage legume or legume mixture (main legume) in each country is also indicated. (From FAOSTAT, 2013; Eurostat, 2013; Annicchiarico *et al.*, 2015.)

Country	Cultivated area (1000 ha) ^a	Proportion of UAA (%)	Mean yield (t/ha) ^b	Main legume ^c
Austria	13.9	0.5	2.4	Red clover
Bosnia-Herzegovina	35.8	2.3	1.8	Red clover
Bulgaria	64.6	2.1	7.1	Lucerne
Croatia	25.9	2.1	2.5	Lucerne
Cyprus	0.8	0.7	3.7	Lucerne
Czech Republic	67.1	1.9	13.7	Lucerne/red clover
Denmark	5.7	0.3	17.6	White clover
Estonia	10.5	1.2	4.5	Red and white clover
France	329.1	1.2	14.8	Lucerne/white clover
Germany	40.4	0.2	11.4	Red clover
Greece	129.3	3.2	3.7	Lucerne
Hungary	132.7	3.0	11.7	Lucerne
Italy	716.4	5.8	10.5	Lucerne
Lithuania	4.8	0.2	7.8	Red clover
Luxembourg	0.3	0.2	13.4	–
Macedonia	18.4	1.9	2.2	Lucerne
Netherlands	5.9	0.3	7.0	White clover
Poland	33.6	0.3	10.4	Red clover
Romania	332.6	2.6	6.0	Lucerne
Serbia	200.0	4.0	5.5	Lucerne
Slovakia	52.2	2.8	10.9	Lucerne
Slovenia	2.6	0.6	2.4	Lucerne/red clover
Spain	248.5	1.1	15.8	Lucerne
Total	2470.9	1.7	10.0	Lucerne

^aAverage for years 2008–2011 according to FAOSTAT, except for: Bosnia-Herzegovina, Croatia, Lithuania, Macedonia (average of 2008–2009) and Greece (2007), which are based on Eurostat; data for Serbia and part of data for France are based on national sources.

^bBased on UAA values for 2010 in Eurostat or other European Union (EU) documents, and reported lucerne growing data.

^cData from Annicchiarico *et al.* (2015).

annual production, are used either in cooler regions or under drought conditions. In temperate climates, lucerne can produce more harvested crude protein per unit area than any grain legume crop (pea, faba bean or soybean) (Huyghe, 2003).

Protein content varies between 15% and 25% of dry matter, depending mainly on the harvest stage. For ruminants, lucerne offers a combination of high voluntary intake, high protein content, good digestibility, and rumen buffering that prevents acidosis. About 10% of lucerne production is used in monogastric animal diets (pigs, poultry, rabbits), where it offers the advantage of high levels of omega-3 fatty acids, carotenoids and mineral nutrients. Lucerne pellets can be included up to 10–20% on a dry matter basis in these diets. This inclusion is limited by either antinutritional compounds and/or excessive fibre content. Introduction

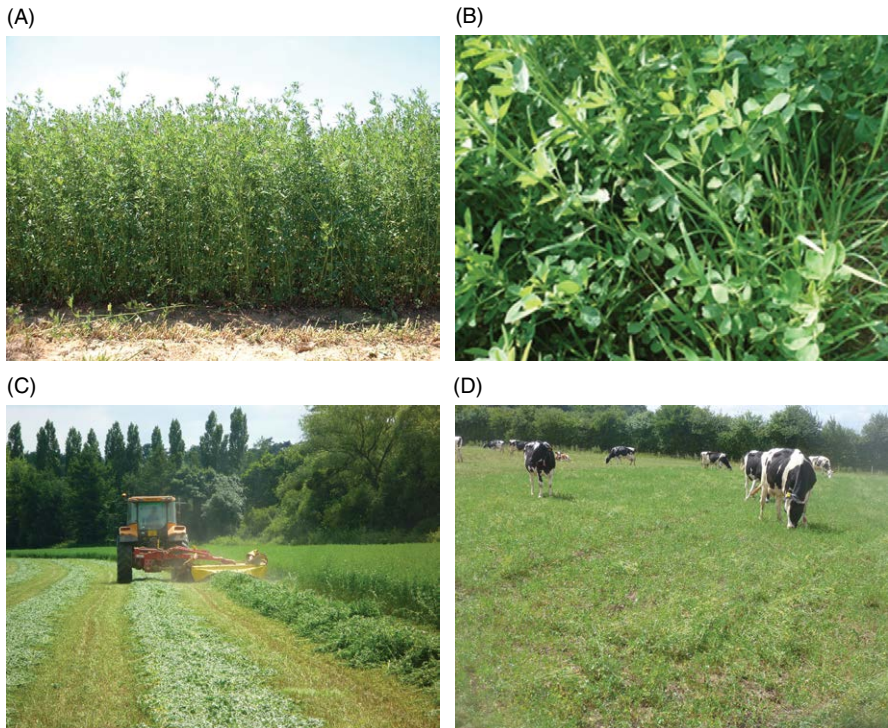


Fig. 11.1. Typical production scenes. (A) Lucerne field at early flowering stage. (B) Lucerne–grass mixture. (C) Mechanical harvest: on the left, some swathes after cutting by only a rotary disc mower and on the right a swathe after cutting with a rotary disc mower with conditioning rollers. (D) Grazing of a lucerne–grass mixture. (Photo credits: B. Julier (A, B) and G. Crocq (C, D).)

of lucerne into the diets of both ruminants and monogastrics is a way to significantly decrease the need for soybean meal.

Cultivation has declined over the last 50 years with the increased cultivation of maize for silage, enabled by a combination of maize breeding, synthetic N fertilization, pesticides and supplementation with soy. Recent increases in fertilizer and soy prices are leading to a reversal of this trend. A return to more mixed farming systems is also contributing to this turnaround.

Genetic Resources

Medicago sativa is a complex of eight diploid or autotetraploid subspecies (Quiros and Bauchan, 1988). The main subspecies are: (i) *sativa* (conventional cultivated lucerne), with purple flowers, a taproot and coiled pods; and (ii) *falcata*, with yellow flowers, fasciculate roots and curved pods. Cultivated material of subsp. *sativa* is tetraploid due to the vigour that tetraploidy confers.

Cultivated lucerne originates from between the Middle East and Central Asia where it may have been cultivated as early as 9000 BC (Sinskaya, 1950). The

history of domestication is not well known. Domestication resulted in an erect growth habit relative to the prostrate habit of wild populations (an adaptation to grazing). Lucerne as a cultivated crop was introduced into Europe with human migrations at various times: through Greece with the Medes, Italy with the Romans, and Spain with the Moors (Fig. 11.2). It became a popular forage species in Europe after the 15th century, from where it was introduced to America. Wild populations of subsp. *sativa* are present in the centre of origin and in Spain, while wild populations of subsp. *falcata* are widespread in Eastern Europe. Most European lucerne cultivars exhibit some degree of introgression from subsp. *falcata* germplasm, which has provided cold tolerance and variable flower colour. Molecular studies show that only 30% of the allele variation in wild populations is also found in cultivated populations (Muller *et al.*, 2006). Persistent feral populations are frequent in Europe and North America, mostly along roadsides (Bagavathiannan *et al.*, 2010). These populations may contain valuable adaptive traits, as suggested by the outstanding frost tolerance of a Canadian feral population.

Several countries in Europe maintain collections of perennial *Medicago* genetic resources, but wild populations are generally poorly represented. The European Cooperative Programme for Plant Genetic Resources (ECPGR), now coordinated by Bioversity International, was set up in 1980 to rationalize the conservation of genetic resources. The perennial *Medicago* collection contains 7874 accessions of 19 species. The Russian Federation hosts one-third of the collection, and tetraploid lucerne represents over 95% of the accessions, including cultivars (1920 accessions), landraces (1430), wild or feral populations (769) and breeding materials (1260).

Lucerne breeding programmes have largely used landrace germplasm adapted to specific environments as their genetic base. These adaptations provide germplasm to counter stresses and to more effectively exploit favourable conditions (Annicchiarico and Piano, 2005). This has a bearing on strategies for locating, evaluating and exploiting genetic resources (Annicchiarico, 2007).

Agronomy, Ecology and Crop Physiology

Establishment

Care in establishing the sward is critical to productivity and longevity of the crop. Summer sowing offers the opportunity to establish the crop just after harvesting the preceding crop. It requires adequate soil humidity and temperature during late summer and autumn so that the lucerne stand is fully established before winter frost. If such favourable conditions are not encountered, the lucerne crop is sown during spring to ensure successful establishment (Mauriès, 2003; Undersander *et al.*, 2011). In any case, effectiveness of plant and sward development in the months after sowing is critical to productivity of the subsequent cropping year. Insufficient sward development from late summer sowing followed by early autumn frosts, reduces production in the following spring.

Lucerne requires well-drained soils and pH above 6 (ideally in the range 6.6–7.5) for optimal growth. Liming is recommended when soil pH is below 6.5. Due



Fig. 11.2. Lucerne introduction into Europe.

to the small size of the lucerne seed, seeding depth is critical and needs to be shallow (typically 1–2 cm). BNF in root nodules requires the presence of specific strains of rhizobia in the soil. Seed inoculation with *Rhizobium meliloti* (or use of inoculated seeds) is essential where there is not a recent history of lucerne cropping.

Lucerne is very susceptible to light competition from weeds during its establishment (Mauriès, 2003; Undersander *et al.*, 2011). A low seedling development due to early intense weed competition is very detrimental to subsequent lucerne production and longevity. Therefore, weed control following sowing is a critical step for proper sward establishment. Weed control can be achieved either chemically (although few herbicides are now permitted) or mechanically. Mixing forage grasses with lucerne may help to reduce and control weed invasion during the establishment phase, provided that the grasses are sown at a density low enough to avoid a level of light competition detrimental to lucerne (Spandl *et al.*, 1999). Lucerne may also be undersown in a cereal (wheat, maize) or an oilseed crop (sunflower) that is harvested for grain, leaving space for the lucerne plants to continue developing and producing during the following years.

Lucerne is an autotoxic species. Lucerne leaves produce water-soluble chemical compounds that leach from crop residues and are retained in the upper soil layer. These inhibit seed germination and seedling development (Chon *et al.*, 2006). This autotoxicity means that an interval of 3–4 years between lucerne crops is required. This also interrupts the cycle of several pests and thus reduces the risks of disease or pest damage.

Dry matter production and leaf area expansion

Under non-limiting conditions, lucerne above-ground growth is linearly related to the amount of solar radiation intercepted by the canopy (Lemaire and Allirand, 1993) (Fig. 11.3). Shortening days and low temperatures in autumn induce allocation of more carbohydrate to roots, explaining the lower radiation use efficiency in terms of above-ground growth observed during this period (Khaity and Lemaire, 1992).

The interception of solar radiation depends on the leaf area index (LAI), which increases linearly with thermal time after each crop harvest. A LAI of 3 (3 m² leaf area/m² ground area) intercepts 90% of incoming light and is reached approximately 300°C days (base 0°C) after mowing under non-limiting conditions (Gosse *et al.*, 1984). In addition to temperature, the residual leaf area left after the harvest and the stage of development of the crown buds also influence the rate of leaf area expansion during regrowth.

Shoot growth and forage quality

As stems elongate, the leaf:stem ratio decreases, which has consequences for the quality of the harvest because leaves have a higher protein content and digestibility

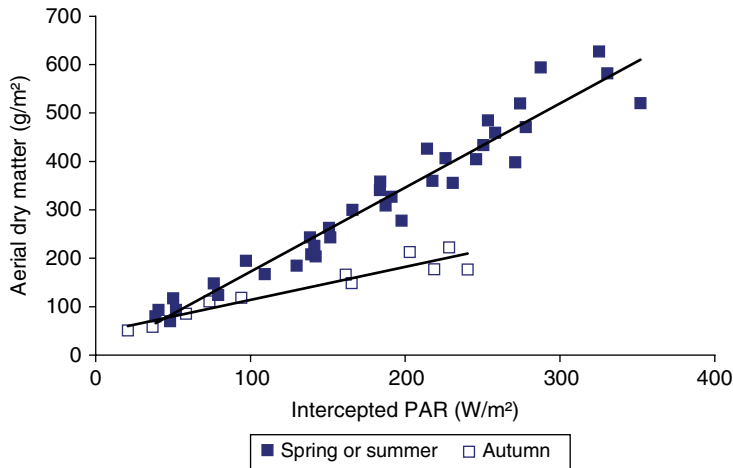


Fig. 11.3. Relationship between above-ground dry matter and the sum of intercepted photosynthetically active radiation (PAR, W/m²) for the spring and summer cuts and for the autumn ones.

than stems (Lemaire and Allirand, 1993) (Fig. 11.4). Late harvests increase yield but decrease the leaf:stem ratio and, hence, the digestibility and N concentration of the harvested biomass.

Short photoperiods and cool temperatures in autumn reduce above-ground growth and favour allocation to roots. During this period, autumn-dormant genotypes produce short decumbent shoots and have higher concentrations of sugars and proteins in their buds and roots than non-dormant genotypes (Cunningham *et al.*, 1998). In autumn, lucerne stems are generally short but very leafy, generating a low forage production but a high forage quality.

Water and nutrient requirements

Lucerne is acknowledged as more drought-tolerant than other perennial legumes because of its deep rooting system (Peterson *et al.*, 1992). However, it is an opportunistic water user that is best suited to soils with a high water reserve. In contrast to species adapted to drought stress, it exhibits low stomatal closure in the early stages of drought (Durand, 2007). After the initial growth phase, BNF in nodulated plants supplies enough fixed N for optimal growth (Lemaire *et al.*, 1985). Annual fixation rates from 85 kg N/ha to 360 kg N/ha are reported (Frame, 2005).

Due to the relatively high yield potential of lucerne under cutting management, large quantities of nutrients are removed in harvested biomass, so particular attention is required to maintain soil fertility in order to achieve high biomass yields (Mauriès, 2003; Undersander *et al.*, 2011). Maintenance of soil fertility is also critical for the longevity of the crop, particularly under poor and acidic soil conditions. Lucerne accumulates potassium (K) and phosphorus (P) at approximately 25 g/kg shoot dry weight and 2.6 g/kg shoot dry weight,

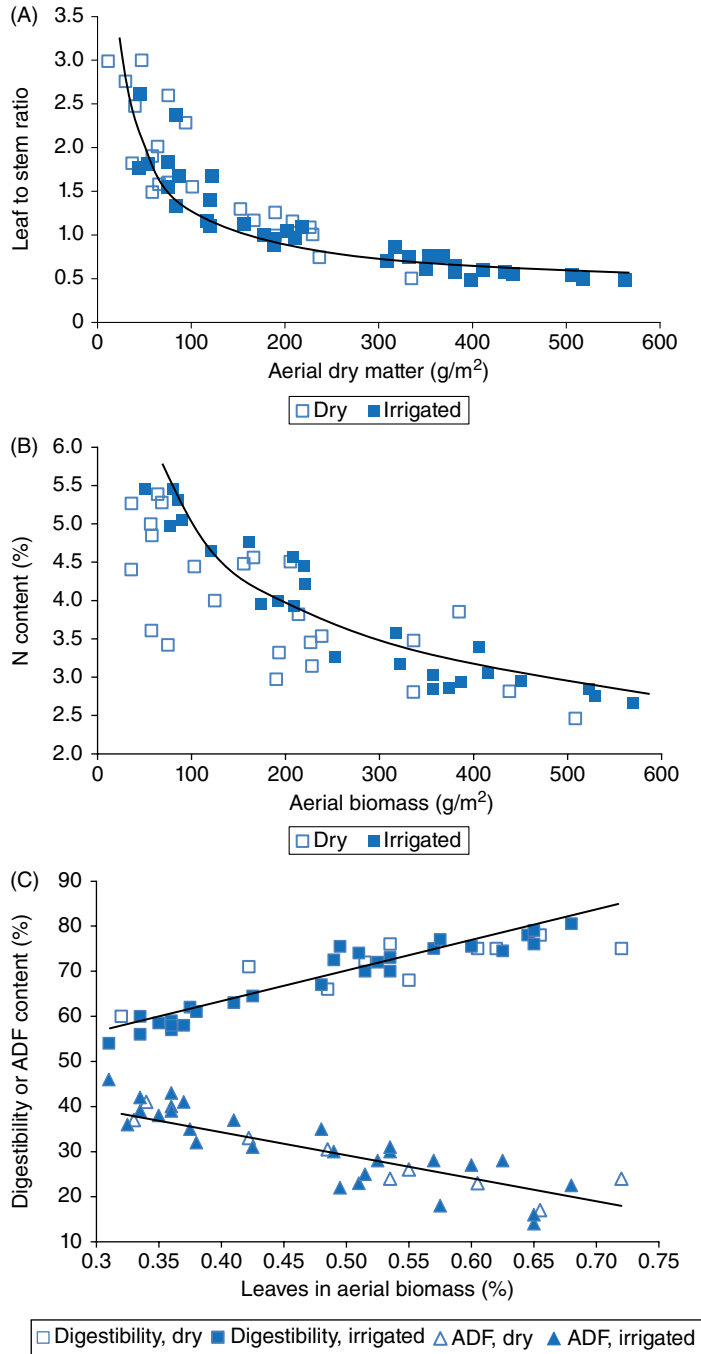


Fig. 11.4. Change in quality traits during dry matter accumulation. (A) Leaf to stem ratio as a function of above-ground dry matter. (B) Nitrogen (N) concentration as a function of above-ground dry matter. (C) Digestibility or acid detergent fibre (ADF) concentration as a function of the percentage of leaves in above-ground biomass. (From Lemaire and Allirand, 1993.)

respectively, corresponding to 30 kg of K_2O /t harvested biomass and 6 kg of P_2O_5 /t harvested biomass. Application of sufficient P and K fertilizers is thus necessary to compensate for these high rates of removal, according to the soil availability of these minerals, which in turn depends on soil physicochemical characteristics and on management of the preceding crops. Similarly, attention to soil availability of other nutrients is required, in particular magnesium, sulfur and calcium, depending on soil characteristics.

Competitive ability and compatibility with grasses

Although lucerne is grown in pure stands in many instances, it is also commonly grown in mixtures with perennial grasses. Mixtures are generally as productive as pure stands under favourable cropping conditions. High-yielding lucerne cultivars in mixtures tend to be at a competitive advantage over grasses (Chamblee and Collins, 1988), so a 50/50 sowing rate frequently results in over 80/20 annual yield in favour of lucerne during the first years. The greater ability of lucerne to compete for light resulting from erect shoots, leaf angles and a large leaf area in the top layers of the canopy partly explains this difference. More balanced mixtures can be achieved through moderate N fertilization to improve grass growth and more frequent defoliation. The choice of grass species and lucerne cultivars is also of importance. Reasonably high-yielding lucerne cultivars with shorter stems, smaller leaves and higher branching ability provide a less aggressive companion crop for the grass (Maamouri *et al.*, 2015). Furthermore, favouring non-competitive interactions in the mixture, such as the transfer on fixed N from the legume to the grass, would also improve grass N nutrition and growth and thus the balance between species. Nevertheless, lucerne displays a rather less efficient N transfer than other forage legumes (Louarn *et al.*, 2015). Although lucerne can fix twice as much N as white clover, white clover is about five times more efficient at providing fixed N to the companion grass than lucerne. A significant diversity in root traits exists among lucerne cultivars, which remains to be exploited in terms of breeding for compatibility with grasses.

Reserves and defoliation management

After harvest, C and N reserves are mobilized from roots for about 6–10 days. Root reserves start to recover after regrowth has progressed but several weeks are generally required to restore them (Lemaire and Allirand, 1993) (Fig. 11.5). Lucerne is thus suited to an infrequent defoliation regime. Furthermore, root N reserves available at harvest influence leaf area expansion and the growth rate after defoliation (Avicé *et al.*, 1997; Justes *et al.*, 2002). Flowering, although not physiologically related to reserve accumulation in the roots, is generally used as an indicator of adequate replenishment of root reserves to guide harvest scheduling. Increasing the mowing frequency reduces the yield of single harvests, the total annual yield and the crop persistence, while increasing the forage nutritive value. For example, in northern France, four harvests are effective, while five are likely to reduce the persistence (Lemaire and Allirand, 1993). Irrigation of lucerne in Mediterranean climates supports up to eight harvests.

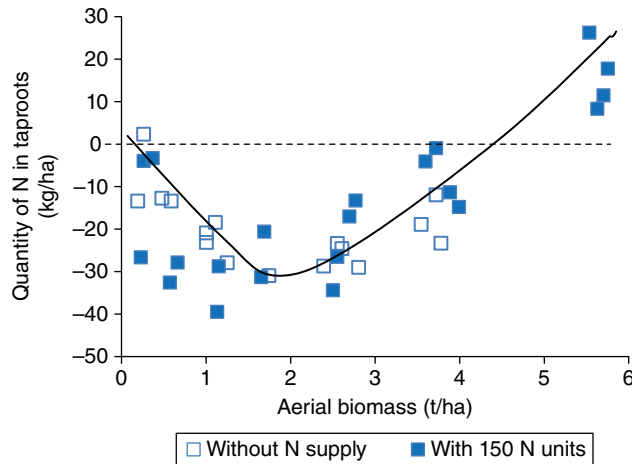


Fig. 11.5. Change of nitrogen (N) content in taproots as a function of above-ground biomass. (From Lemaire and Allirand, 1993.)

Breeding

Genetic progress

The rate of genetic progress for lucerne forage quality has been modest, namely, 0.2–0.3% per year in the USA and somewhat less in Europe (up to 0.15% per year) (Annicchiarico *et al.*, 2015), which is definitely lower than major grain crops such as wheat or maize. Recent breeding advance relates mainly to greater tolerance to major pests. Breeding progress for intrinsic yield potential is slow due to the perennial nature of the crop, long breeding cycles, and because increasing the harvest index is not a breeding option as it is in cereals. Breeding is also difficult because cultivars are populations rather than pure lines.

Cultivar structure

The biological characteristics (allogamy, impossibility to control pollination and inbreeding depression) facilitate the breeding of synthetic cultivars that exploit heterosis. Each cultivar is derived from four to 200 parents (a parent being an individual genotype, or a half-sib progeny obtained by open-pollination of one mother plant). Three to four generations of polycrossing (or inter-mating) are made to obtain the commercial seed. A cultivar is thus a population of related genotypes.

The only commercial genetically modified (GM) lucerne cultivar is a Roundup Ready cultivar registered in the USA in 2005 (which underwent a period of legal confrontation before being admitted to cultivation). A second GM cultivar with improved digestibility has been obtained by down-regulating lignin synthesis (Guo *et al.*, 2001; McCaslin and Reisen, 2012). The development of GM lucerne cultivars in Europe is expected to be met with public hostility strengthened by

the risk of gene flow to feral or wild populations due to the reproductive system. However, for a few crucial traits that show no variation within lucerne, such as tannin content, a GM cultivar could be a real breakthrough.

Breeding targets

Autumn dormancy is important for winter survival. The cultivars adapted to northern Europe have a dormancy class ranging from 3 to 5 on a scale from 1 to 11. Cultivars adapted to European Mediterranean climates have a dormancy of 6 to 8. Within each dormancy class, breeding targets are mostly similar with some differences in emphasis. Forage yield is a major target. It is frequently tested over 2 production years (not including the sowing year). Stem length is an important trait, although stem diameter and stem number tend to compensate each other. Resistance to lodging is important, especially in the spring cuts for northern Europe, because it ensures that all the above-ground biomass is harvested. It is strongly related to stem diameter, a trait that is negatively correlated with voluntary intake by small ruminants.

Forage quality is also evaluated, with emphasis on protein content and fibre content. Even if quality traits tend to correlate negatively with forage yield, genetic variation is available (Julier *et al.*, 2000) and cultivars with high digestibility improve milk production in dairy cows (Emile *et al.*, 1997). Seed production is also important for propagation. The seed weight per inflorescence is a useful breeding criterion in selecting for high seed yield (Bolaños-Aguilar *et al.*, 2001).

Resistance to diseases is a major target, with genetic progress attained for response to verticillium wilt (*Verticillium albo-atrum*) and anthracnose (*Colletotrichum trifolii*). Resistance to stem nematode (*Ditylenchus dipsaci*) is also important. Tests in controlled conditions are available for all of these biotic stresses (Leclercq and Caubel, 1991; Julier *et al.*, 1996; Molinéro-Demilly *et al.*, 2007). Tolerance to other biotic stresses may be needed for specific adaptation. Screening tests in controlled conditions have been proposed for resistance to aphids (Girousse and Bournoville, 1994; Landré *et al.*, 1999) and sclerotinia rot (*Sclerotinia trifoliorum*) (Julier *et al.*, 1996).

Drought is a major constraint on yield, although drought tolerance has been only a minor breeding target so far. In most European regions, lucerne frequently experiences transient drought episodes during which an important objective is to maintain sufficient forage production. Modest levels of irrigation are used in southern Europe but the crop is not a priority where irrigation water is scarce. Genetic variation for adaption to drought or moisture-favourable conditions is wide in lucerne (Annicchiarico and Piano, 2005; Annicchiarico *et al.*, 2011). Different and partly incompatible morpho-physiological traits are associated with optimal plant adaptation to drought-prone and moisture-favourable conditions (Annicchiarico *et al.*, 2013).

Despite the degree to which acidic soils limit lucerne cultivation in Europe, no selection has been carried out to improve tolerance to low pH. Other legume species (clovers) are preferred for low pH soils. Cultivars that are tolerant of salinity have been developed in the USA, whereas salt-tolerant landraces evolved in

Northern Africa where saline conditions are relatively frequent (Annicchiarico *et al.*, 2011).

The development of low-input farming systems has implications for breeding targets. These include: (i) breeding for adaptation to mixed lucerne–grass cultivation; (ii) adaptation to grazing, which is favoured by less erect growth habit and other characteristics which can conveniently be introgressed from *falcata* germplasm (Pecetti *et al.*, 2008); and (iii) high ability to compete with weeds, to reduce reliance on herbicides (Annicchiarico and Pecetti, 2010).

Breeding schemes

In most cases, lucerne breeding pools are composed of polycross progenies and new germplasm (landraces or cultivars). This plant material may be submitted to disease tests, selecting resistant plants for evaluation in a field nursery under spaced planting conditions or relatively dense conditions. In this design, the most heritable traits (plant height, lodging) and the traits that show a large within-family variation (digestibility, protein content, seed weight per inflorescence) are scored.

Breeding programmes frequently adopt a final stage selection for the best individuals, identifying the parents of future synthetic cultivars according to forage yield and quality traits of their half-sib progenies grown in dense, replicated micro-plots. Either the best parent plants or, less frequently, the best half-sib progenies (or the best plants within each progeny) are used to produce the first generation of a candidate cultivar (or possibly for entering a new cycle of recurrent selection). Multi-site trials can be used for testing the candidate cultivar or, when more than one candidate cultivar is available, for selecting one for registration in a national list of cultivars.

Up to now, the use of molecular markers in breeding programmes has been very limited. However, some results and prospects show that molecular tools, including genomic selection, should soon contribute to the genetic progress (Annicchiarico *et al.*, 2015).

Agronomical Role and Environmental Impacts of Lucerne

Beneficial role of lucerne in crop rotations

The benefits of lucerne in crop rotations arise from the ability to improve soil fertility and soil structure and to limit weed development in subsequent crops. Lucerne accumulates large amounts of N, commonly 300–400 kg/ha/year (Kelner *et al.*, 1997; Angus and Peoples, 2012). Up to 165 kg/ha of N are accumulated in the crown and roots (Rasse *et al.*, 1999; Justes *et al.*, 2001), which is available to subsequent crops. The N fertilizer replacement value of lucerne for subsequent crops is generally estimated at 100–200 kg/ha (Baldock *et al.*, 1981; Bruulsema and Christie, 1987; Hesterman *et al.*, 1987; Ballesta and Lloveras, 2010). A significant residual N effect of lucerne is also observed in the second cereal cropping year (Cela *et al.*, 2011; Vertès *et al.*, 2015).

Lucerne N rhizodeposition has been estimated to account for 3–5% of fixed N, a value which appears to be lower than for several other legumes (Brophy and Heichel, 1989; Lory *et al.*, 1992). Rhizodeposition is particularly low during the first year of lucerne cultivation (Heichel and Henjum, 1991). Lucerne rhizodeposition appears to be more related to changes in plant density and turnover of fine roots than to turnover of nodules (which are indeterminate) or to root exudation (Brophy and Heichel, 1989; Dubach and Russelle, 1994; Louarn *et al.*, 2015). Therefore, rhizodeposition during the growth phase appears to have a limited contribution to the residual N effects of this species, and the low values account for the low N transfer to grasses.

Approximately 25–35% of the crop residue is mineralized during the first year following the crop destruction (Angus *et al.*, 2006). The relatively slow initial decomposition rate of taproot and other thick roots probably explains the low initial mineralization rate of lucerne residues, along with the long overall duration of N release spanning several years. Crop destruction during the autumn is more favourable for mineral N release to a subsequent spring crop than the destruction during late winter, due to the longer period of N mineralization before establishment of the spring crop (Angus *et al.*, 2000).

In rotations, lucerne has a positive effect on subsequent crops through its capacity to improve soil structure and soil permeability. However, the ability of lucerne to take up water from deep in the subsoil through its extensive root system may lead to water deficit of the subsequent crop during its early growth under limited rainfall (Angus *et al.*, 2000).

Effects of lucerne on the environment

Lucerne can take up nitrate from deep soil layers (Blumenthal and Russelle, 1996). The risk of nitrate leaching below the lucerne crop is generally very low, even where manure is applied (Thiébeau *et al.*, 2004). Lucerne is considered an efficient forage species for nitrate-enriched soils (Russelle *et al.*, 2007). Emissions of nitrous oxide (N₂O) have been observed in the range 0.67–1.45 kg of N₂O-N/ha/year (Rochette *et al.*, 2004), which is intermediate between the lower emission rates of unfertilized grass and the higher emission rates of well-fertilized crops. However, higher N₂O emissions have been reported in succeeding crops (Wagner-Riddle and Thurtell, 1998). Lucerne crops accumulate significant amounts of C in the soil (Mortenson *et al.*, 2004) contributing to mitigation of C emissions.

Biodiversity (insects, birds, small mammals)

Lucerne is recognized as a key habitat for many species in mixed farming systems. In France, 40 insect species have been reported in lucerne (Raynal *et al.*, 1989) as potential pests for forage or seed production, but little is known about effects on lucerne production in natural conditions where biological interactions may regulate their abundance. A recent study in western France (Long Term Ecological Research (LTER) network, 'Zone Atelier Plaine et Val de Sèvre') identified more

than 30 wild bee species in flowering lucerne crops, against ten concurrently found in sunflower crops (Rollin *et al.*, 2013).

Lucerne crops are also important habitats for other important taxa such as grasshoppers (Badenhausser *et al.*, 2012) and small mammals (common vole and mouse species) that use lucerne for overwintering and reproduction (Inchausti *et al.*, 2009). The abundance of these prey species drives the population dynamics of their predators at the landscape scale. An increase in the area of lucerne benefits skylarks (Kragten *et al.*, 2008), ortolan bunting (Morelli, 2012) and top predators, such as raptors (e.g. Montagu's harrier) (Salamolard *et al.*, 2000) or the little bustard (Bretagnolle *et al.*, 2011), which are birds of high conservation value. Some agri-environmental schemes support lucerne production (Berthet *et al.*, 2012). While butterfly species richness per field was 5.6 species in conventional lucerne fields in eastern France, it reached 8.8 species in lucerne managed to favour butterflies (Thiébeau *et al.*, 2010). Grasshopper densities in agri-environment scheme (AES) lucerne fields can be fourfold higher than in conventional fields (Fig. 11.6). The management of lucerne fields at the local and landscape scales is critical for both the maintenance of ecosystem services, such as those depending on functional biodiversity, and the conservation of threatened species.

Weeds

Weeds can be a problem in lucerne, particularly at establishment but also after each cutting. Approved herbicides are available. The introduction of lucerne into

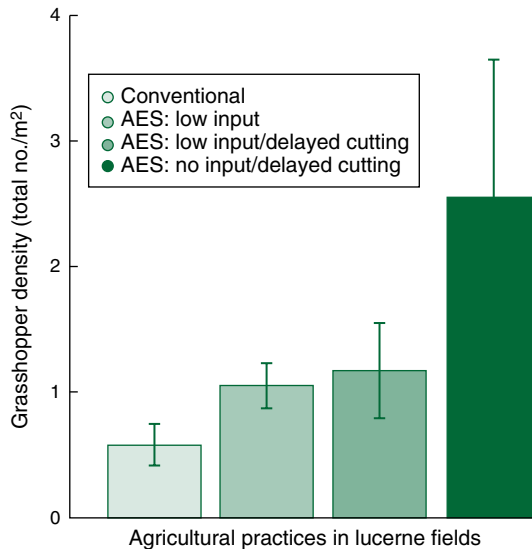


Fig. 11.6. Grasshopper density (all species cumulated) in conventional and agri-environment scheme (AES) lucerne fields (total number/m² ± standard error) in the Long Term Ecological Research (LTER) network 'Zone Atelier Plaine et Val de Sèvre'.

the rotation induces a change in the weed flora, with less climbing and erect annual dicots and more perennial dicots and annual rosette dicots. Therefore, including lucerne in rotations can reduce the risk of weeds affecting subsequent annual crops. Lucerne–grass mixtures can be used to reduce the risk of weed problems. From a breeding perspective, competitive ability against weeds is correlated with yield potential (Annicchiarico and Pecetti, 2010). Using mixtures of lucerne and annual legumes is also a way to decrease the development of weeds in the establishment year of lucerne while increasing forage production (see Chapter 12, this volume).

Harvest

Grazing

Grazing is not popular in Europe but is common in North and South America. It is the cheapest way to harvest forage. Rotational grazing is generally more convenient than continuous grazing, and should be limited to a few days, to reduce damage to new stems. Grazing-tolerant cultivars are required to maintain satisfactory persistence. The soil should be dry enough to prevent poaching which may cause serious damage to the plants. The grazing interval should be at least 35 days to enable the recovery of root reserves. In the south of France, autumn regrowth provides a high-quality forage that is utilized by sheep or goats. Breeding and selection increases grazing tolerance, allowing continuous grazing for cattle and sheep (Annicchiarico *et al.*, 2010).

In some conditions (wet forage, high protein content, animals not accustomed to lucerne), foaming occurs in the rumen and may cause animal death, and this is a major disadvantage for many farmers. However, several management practices can minimize these risks: (i) grazing of Lucerne–grass mixture; (ii) no grazing in the early morning when the plants are still wet; and (iii) the use of anti-foaming agents.

Silage and hay

The choice of the cutting schedule is critical for yield, quality and persistency. Generally, the first cut of the year is conducted at budding stage and followed by cuts at 5- to 8-week intervals to maximize yield, give satisfactory nutritive value and support persistence. In Western Europe, 1–3 days of wilting are needed to make silage, 2–4 days to store in wrapped bales (about 40–50% moisture when the forage is wrapped) and 3–6 days to make hay (below 20% moisture). Silage is generally convenient for the first cut, when the quantity of forage is high enough to make a silo and the weather is not dry or warm enough for natural drying. Because of the high protein content, low sugar content and high buffering capacity, silage requires pre-wilting of the forage so that it is ensiled at a minimum of 35% dry matter. The sugar content affects preservation. It is higher at the budding stage than at flowering stage (6–10% compared with less than 5%) and at the end

of the day than in the morning. Rapid wilting limits respiration and sugar losses. If the dry matter content of lucerne is lower than 35%, silage making requires the addition of either preservatives, other sources of sugar (e.g. a sugar-rich forage grass or molasses) or dry components such as dried sugarbeet pulp.

Wrapped bales are also used to make silage. Two conditions are needed to limit the development of butyric microorganisms that represent the main risk for preservation in wrapped bales: (i) no soil in the bales (obtained by a harvest height of at least 6–8 cm); and (ii) a dry matter content of 50–60%. The bale density must reach about 200 kg of dry matter/m³. Depending on the water content of the forage in the bales, nutritive value of wrapped bales is higher than hay and may be similar to conventional silage.

Hay making is a traditional way to conserve lucerne, but skill is required to avoid field losses that can reach as high as 30%. Leaves dry quicker than stems and the nutritional composition of hay drops if leaves are lost during hay making. In humid environments, a morning mowing is recommended to benefit from the whole first day and increased drying rate. Roll conditioners crush the stems and enable faster and better synchronized drying of stems and leaves. Tedding and raking must be confined to early in the morning when the forage is still wet with dew to reduce leaf losses. All these methods still present a risk of low-quality forage and are time-consuming. Barn-drying has proved to be efficient but requires specific investment. Briefly, pre-wilted forage (60–65% of dry matter) is stored in a chamber and warm air is blown in and progressively dries it. The air may be heated using solar energy absorbed by the roof. A high-quality hay is obtained. For dehydration, factories establish contracts with lucerne growers and organize cutting and dehydration schedules. The stage of plant development, the distance from field to factory and the age of lucerne field are taken into account. Intervals between cuts are 40–50 days, depending on crop growth and the objectives of production (high protein and energy contents or high fibre content). During the lucerne harvest period (April–October), the factory works round the clock, while other crops or by-products are dehydrated in the other seasons. Thirty years ago, lucerne forage was delivered to the factory soon after mowing and was dehydrated at 600–800°C. In order to limit energy consumption, forage is now pre-wilted in the field before dehydration, and the drying temperature is close to 250°C, which is sufficient to produce a Maillard reaction between sugars and proteins, thereby limiting the protein degradability in the rumen and increasing the protein value of the crop.

Lucerne in Farming Systems

In mixed animal–crop production systems, lucerne or lucerne–grass mixtures are cultivated in rotation with annual crops devoted to animal nutrition (maize, cereals) and possibly with annual cash crops. Lucerne cropping is also introduced into annual cropping systems on stock-less farms and is traded as hay. Traditionally, these exchanges occur at a local scale between farmers. They are currently emerging at a larger regional scale, with the involvement of brokers such as cooperatives. Trade also occurs at the intercontinental level. Some

countries such as China and Saudi Arabia import large quantities of compressed lucerne hay from California to support livestock production. To our knowledge, European producers of lucerne are not present in this international market of lucerne hay.

Feeding Value for Ruminants and Monogastrics

Ruminants

Lucerne is of high interest for ruminant feeding because of its high dry matter yield, protein and calcium contents, palatability and high level of intake. It has also a well-balanced amino-acid profile and provides higher amounts of minerals and vitamins than other forages. It is a flexible forage resource that can be grazed, fed as green forage, offered as hay or silage, or given as dehydrated roughage (Baumont *et al.*, 2014).

For dairy cattle, grazing can support up to 25 kg milk/day from an intake of 20 kg dry matter/day saving 1 kg soybean meal/day (Heuzé *et al.*, 2013). Given as fresh forage or as silage, it can replace up to 50% of a maize silage diet, enriching the diet in protein and minerals, avoiding metabolic disorders and reducing the use of concentrate feeds. Hay feeding alone supports 27 kg milk/day with up to 45 kg milk/day produced when it is supplemented with concentrate feed. Dehydrated lucerne can partially replace protein-rich concentrates in dairy cow diets, allowing high levels of production. In beef production, grazing needs supplementation with either grass hay (4–8 kg/day) or cereals (2–5 kg/day) to support high growth rates (up to 1.8 kg/day). Lucerne can also be used for feeding small ruminants such as sheep and goats, for either milk or meat production. High-quality lucerne hay and pellets are well suited for high-production animals while lucerne silage could be offered to lower-requirement animals.

The main difficulties for the farmers – and challenges for the future – are: (i) to protect lucerne from over-grazing; (ii) to get the best compromise between dry matter yield and quality; and (iii) to limit the high protein degradation rate.

The water-soluble carbohydrate:protein ratio is higher in lucerne–grass mixtures than in pure lucerne (da Silva *et al.*, 2013), and this increases the utilization of the protein (N) component. Combining lucerne with some grasses is generally a good approach to utilization.

Pigs and poultry

For monogastric feeding, lucerne is generally incorporated at a low percentage of the diet (Heuzé *et al.*, 2013). Its fibre content is high and limits animal growth rate. Its protein and also its mineral contents are valuable. The saponins have an anti-cholesterolemic effect and may reduce animal growth rate, even though a positive effect has been reported on the reduction of cholesterol content of animal products (Ostrowski-Meissner *et al.*, 1995). Carotenoids have a positive impact

on the pigmentation of eggs and body lipids of poultry. Finally, the proportion of lucerne introduced in the diets of pigs or poultry is usually lower than 10–15% and is mainly composed of dehydrated products. For rabbits, the inclusion of lucerne is much more important. A rate of 40–60% of lucerne in the diet, as hay or pellets, is frequently recommended.

Novel and Non-food Use

Certain concentrated lucerne components are useful for animal health or animal quality products, human health, cosmetology, energy production and pet health.

Protein concentrates that are also rich in minerals and vitamins are produced from lucerne juice obtained after pressing and precipitation. They are distributed to fight against malnutrition in Africa and South America but could also be used for people suffering from protein deficiency. They have obtained the 'Novel food' label from the European Food Security Agency in 2009 as they may have the beneficial effects of ten out of 16 classes of food supplements. For ruminant production, the omega-3 fatty acids in lucerne could be used to improve the quality of animal production (milk and meat). The saponins that are naturally present can be used to reduce methane production in cattle (Beauchemin *et al.*, 2009; Malik and Singhal, 2009). Minerals and vitamins of lucerne can also be used for cosmetics and skincare. Research is being carried out to define dietary products to reduce or prevent obesity of companion animals.

Lucerne may also be used for energy production because of its high biomass production and its low N fertilization requirement. Energy production is based on the exploitation of cell wall polysaccharides, but a low N content is preferred to avoid greenhouse gas emissions. Integrated or cascade uses start with protein extraction for animal feeding or human supplement and then the polysaccharide residue is used as a source of biomass energy. In such a system, labour costs might be reduced because a longer regrowth period and lower plant density could be used to combine high yield with limited senescence of leaves (Lamb *et al.*, 2003). Specific cultivars, with an erect growth habit, thick stems and resistance to lodging, would be appropriate for this type of use (Lamb *et al.*, 2007).

Seed Production

Lucerne seed is mainly produced in the USA, Canada, Australia and Europe (France, Italy, Spain, Hungary and Serbia) (Boelt *et al.*, 2015). The favourable regions are characterized by a deep soil with high water reserves combined with summers that are warm and dry to ensure optimal seed maturation and harvest. Sowing density is lower than for forage production (4 kg of seed/ha) and rows are wider (around 0.35 m). Usually, the stands are clipped early in spring, so that lodging risk is reduced and flowering date coincides with bee activity that is further enhanced by dry conditions in late spring or early

summer. Insecticide is often needed to avoid seed losses. Optimal management of lucerne seed production crops resulted in an increase in seed production from 200 kg/ha to 500 kg/ha in France in the past 30 years (Hacquet and Karagic, 2014).

Seed production has always been an important aspect of lucerne cultivation. In the past, seed exchanges or marketing were observed within a region, a country or overseas without strict control of the origin of the cultivar or the population (Julier *et al.*, 1996). Nowadays, seed yield influences seed prices and the commercial success of a cultivar is influenced by seed price, so a cultivar that is very good for forage production but poor for seed production is usually not available to the farmers. A significant international market for seed exists, with world trade dominated by exports from North America and Australia (Le Buanec, 1997; Huyghe, 2005).

Outlook

Lucerne has many advantages as a source of forage for animal feeding. Its high forage production and high protein content are combined with low N fertilization requirements, adequate persistence and beneficial agronomical effects on the following crop. Recent scientific studies have confirmed the renowned positive environmental impact of lucerne cropping. Actions are required to safeguard the cultivation of lucerne and boost its positive effects for European agriculture.

The Common Agricultural Policy in 2013 established that member states devoted 2% of Single Farm Payments to revive the production of protein-rich feed crops. To be efficient, this protein plan requires: (i) research and development to increase forage yield; (ii) development of processes for the medium scale; (iii) encouragement and support for the establishment of contracts between lucerne producers and users; (iv) information and extension; (v) development of programmes for livestock farmers, aimed at promoting multifunctional forage systems; and (vi) economic support to compensate for the lower financial returns for lucerne related to environmental benefits.

References

- Angus, J.F. and Peoples, M.B. (2012) Nitrogen from Australian dryland pastures. *Crop and Pasture Science* 63, 746–758.
- Angus, J.F., Gault, R.R., Good, A.J., Hart, A.B., Jones, T.D. and Peoples, M.B. (2000) Lucerne removal before a cropping phase. *Australian Journal of Agricultural Research* 51, 877–890.
- Angus, J.F., Bolger, T.P., Kirkegaard, J.A. and Peoples, M.B. (2006) Nitrogen mineralisation in relation to previous crops and pastures. *Australian Journal of Soil Research* 44, 355–365.
- Annicchiarico, P. (2007) Wide- versus specific-adaptation strategy for lucerne breeding in northern Italy. *Theoretical and Applied Genetics* 114, 647–657.
- Annicchiarico, P. and Pecetti, L. (2010) Forage and seed yield response of lucerne cultivars to chemically weeded and non-weeded managements and implications for germplasm choice in organic farming. *European Journal of Agronomy* 33, 74–80.

- Annicchiarico, P. and Piano, E. (2005) Use of artificial environments to reproduce and exploit genotype \times location interaction for lucerne in northern Italy. *Theoretical and Applied Genetics* 110, 219–227.
- Annicchiarico, P., Scotti, C., Carelli, M. and Pecetti, L. (2010) Questions and avenues for lucerne improvement. *Czech Journal of Genetics and Plant Breeding* 46, 1–13.
- Annicchiarico, P., Pecetti, L., Abdelguerfi, A., Bouizgaren, A., Carroni, A.M., Hayek, T., M'Hammadi Bouzina, M. and Mezni, M. (2011) Adaptation of landrace and variety germplasm and selection strategies for lucerne in the Mediterranean Basin. *Field Crop Research* 120, 283–291.
- Annicchiarico, P., Pecetti, L. and Tava, A. (2013) Physiological and morphological traits associated with adaptation of lucerne (*Medicago sativa* L.) to severely drought-stressed and to irrigated environments. *Annals of Applied Biology* 162, 27–40.
- Annicchiarico, P., Barrett, B., Brummer, E.C., Julier, B. and Marshal, A.H. (2015) Achievements and challenges in improving temperate perennial forage legumes. *Critical Reviews in Plant Sciences* 34, 327–380.
- Avicé, J.C., Lemaire, G., Ourry, A. and Boucaud, J. (1997) Effects of the previous shoot removal frequency on subsequent shoot regrowth in two *Medicago sativa* L. cultivars. *Plant Soil* 188, 189–198.
- Badenhausser, I., Gouat, M., Goarant, A., Cornulier, T. and Bretagnolle, V. (2012) Spatial autocorrelation in farmland grasshopper (Orthoptera: Acrididae) assemblages in Western France. *Environmental Entomology* 41, 1050–1061.
- Bagavathiannan, M.V., Gulden, R.H., Begg, G.S. and Van Acker, R.C. (2010) The demography of feral alfalfa (*Medicago sativa* L.) populations occurring in roadside habitats in Southern Manitoba, Canada: implications for novel trait confinement. *Environmental Science and Pollution Research* 17, 1448–1459.
- Baldock, J.O., Higgs, R.L., Paulson, W.H., Jackobs, J.A. and Shrader, W.D. (1981) Legume and mineral N-effects on crop yields in several crop sequences in the upper Mississippi valley. *Agronomy Journal* 73, 885–890.
- Ballesta, A. and Lloveras, J. (2010) Nitrogen replacement value of alfalfa to corn and wheat under irrigated Mediterranean conditions. *Spanish Journal of Agricultural Research* 8, 159–169.
- Baumont, R., Heuzé, V., Tran, G. and Boval, M. (2014) Alfalfa in ruminant diets. *Legume Perspectives* 4, 36–37.
- Beauchemin, K.A., McAllister, T.A. and McGinn, S.M. (2009) Dietary mitigation of enteric methane from cattle. *CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources* 4, No. 035, 1–18.
- Berthet, E., Bretagnolle, V. and Segrestin, B. (2012) Analyzing the design process of farming practices ensuring little bustard conservation: lessons for collective landscape management. *Journal of Sustainable Agriculture* 36, 319–336.
- Blumenthal, J.M. and Russelle, M.P. (1996) Subsoil nitrate uptake and symbiotic dinitrogen fixation by alfalfa. *Agronomy Journal* 88, 909–915.
- Boelt, B., Julier, B., Karagic, Đ. and Hampton, J. (2015) Legume seed production, meeting market requirements and economic impacts. *Critical Reviews in Plant Sciences* 34, 412–427.
- Bolaños-Aguilar, E.D., Huyghe, C., Djukic, D., Julier, B. and Ecalle, C. (2001) Genetic control of alfalfa seed yield and its components. *Plant Breeding* 120, 67–72.
- Bretagnolle, V., Villers, A., Denonfoux, L., Cornulier, T., Inchausti, P. and Badenhausser, I. (2011) Rapid recovery of a depleted population of little bustards *Tetrax tetrax* following provision of alfalfa through an agri-environment scheme. *Ibis* 153, 4–13.
- Brophy, L.S. and Heichel, G.H. (1989) Nitrogen release from roots of alfalfa and soybean grown in sand culture. *Plant and Soil* 116, 77–84.
- Bruulsema, T.W. and Christie, B.R. (1987) Nitrogen contribution to succeeding corn from alfalfa and red clover. *Agronomy Journal* 79, 96–100.

- Cela, S., Santiveri, F. and Lloveras, J. (2011) Optimum nitrogen fertilization rates for second-year corn succeeding alfalfa under irrigation. *Field Crops Research* 123, 109–116.
- Chamblee, D.S. and Collins, M. (1988) Relationships with other species in a mixture. In: Hanson, A.A., Barnes, D.K. and Hill, R.R. (eds) *Alfalfa and Alfalfa Improvement*. American Society of Agronomy, Madison, Wisconsin, pp. 439–461.
- Chon, S.U., Jennings, J.A. and Nelson, C.J. (2006) Alfalfa (*Medicago sativa* L.) autotoxicity: current status. *Allelopathy Journal* 18, 57–80.
- Cunningham, S.M., Volenec, J.J. and Teuber, L.R. (1998) Plant survival and root and bud composition of alfalfa populations selected for contrasting fall dormancy. *Crop Science* 38, 962–969.
- da Silva, M.S., Tremblay, G.F., Bélanger, G., Lajeunesse, J., Papadopoulos, Y.A., Fillmore, S.A.E. and Jobim, C.C. (2013) Energy to protein ratio of grass–legume binary mixtures under frequent clipping. *Agronomy Journal* 105, 482–492.
- Dubach, M. and Russelle, M.P. (1994) Forage legume roots and nodules and their role in nitrogen transfer. *Agronomy Journal* 86, 259–266.
- Durand, J.L. (2007) Effects of water shortage on forage plants. *Fourrages* 190, 181–196.
- Emile, J.C., Mauries, M., Allard, G. and Guy, P. (1997) Genetic variation in the feeding value of alfalfa genotypes evaluated from experiments with dairy cows. *Agronomie* 17, 119–125.
- Eurostat (2013) Eurostat. European Commission, Brussels. Available at: <http://ec.europa.eu/eurostat> (accessed 5 November 2013).
- FAOSTAT (2013) Statistics Database of the Food and Agriculture Organization of the United Nations. Food and Agriculture Organization of the United Nations, Rome. Available at: <http://faostat3.fao.org/home/E> (accessed 5 November 2013).
- Frame, J. (2005) *Forage Legumes for Temperate Grasslands*. Science Publishers Inc., Einfeld, New Hampshire.
- Girousse, C. and Bournoville, R. (1994) Biological criteria of the pea aphid *Acyrtosiphon pisum* Harris and varietal resistance of lucerne. In: Eucarpia section of *Management and Breeding of Perennial Lucerne for Diversified Purposes*, Lusignan, France, 4–8 September 1994. Food and Agriculture Organization of the United Nations (FAO), Rome, pp. 251–253.
- Gosse, G., Chartier, M. and Lemaire, G. (1984) Mize au point d'un modèle de prévision de production pour une culture de luzerne. *Comptes Rendus de l'Académie des Sciences Série III* 298, 541–544.
- Guo, D.G., Chen, F., Wheeler, J., Winder, J., Selman, S., Peterson, M. and Dixon, R.A. (2001) Improvement of in-rumen digestibility of alfalfa forage by genetic manipulation of lignin O-methyltransferases. *Transgenic Research* 10, 457–464.
- Hacquet, J. and Karagic, D. (2014) Alfalfa management for higher and more sustainable seed yields. *Legume Perspectives* 4, 34–35.
- Heichel, G.H. and Henjum, K.I. (1991) Dinitrogen fixation, nitrogen transfer and productivity of forage legume–grass communities. *Crop Science* 31, 202–208.
- Hesterman, O.B., Russelle, M.P., Sheaffer, C.C. and Heichel, G.H. (1987) Nitrogen utilization from fertilizer and legume residues in legume–corn rotations. *Agronomy Journal* 79, 726–731.
- Heuzé, V., Tran, G., Boval, M., Lebas, F., Lessire, M., Noblet, J. and Renaudeau, D. (2013) Alfalfa (*Medicago sativa*). Feedipedia.org. A programme by Institut National de la Recherche Agronomique (INRA), Centre de coopération Internationale en Recherche Agronomique pour le Développement (CIRAD), Association Française de Zootechnie (AFZ) and the Food and Agriculture Organization of the United Nations (FAO). Available at: <http://www.feedipedia.org/node/275> (last updated on 9 December 2013) (accessed 28 January 2014).
- Huyghe, C. (2003) Les fourrages et la production de protéines. *Fourrages* 174, 145–162.
- Huyghe, C. (2005) *Prairies et Cultures Fourragères en France*. INRA Editions, Paris, 228 pp.
- Inchausti, P., Carslake, D., Attié, C. and Bretagnolle, V. (2009) Is there direct and delayed density dependent variation in population structure in a temperate European cyclic vole population? *Oikos* 118, 1201–1211.

- Julier, B., Guy, P., Castillo-Acuna, C., Caubel, G., Ecalte, C., Esquibet, M., Furstoss, V., Huyghe, C., Lavaud, C., Porcheron, A., Pacros, P. and Raynal, G. (1996) Genetic variation for disease and nematode resistances and forage quality in perennial diploid and tetraploid lucerne populations (*Medicago sativa* L.). *Euphytica* 91, 241–250.
- Julier, B., Huyghe, C. and Ecalte, C. (2000) Within- and among-cultivar genetic variation in alfalfa: forage quality, morphology, and yield. *Crop Science* 40, 365–369.
- Justes, E., Thiébeau, P., Cattin, G., Larbre, D. and Nicolardot, B. (2001) Libération d'azote après retournement de luzerne. Un effet sur deux campagnes. *Perspectives Agricoles* 264, 22–28.
- Justes, E., Thiébeau, P., Avice, J.C., Lemaire, G., Volenec, J.J. and Ourry, A. (2002) Influence of summer sowing dates, N fertilization and irrigation on autumn VSP accumulation and dynamics of spring regrowth in alfalfa (*Medicago sativa* L.). *Journal of Experimental Botany* 53, 111–121.
- Kelner, D.J., Vessey, J.K. and Entz, M.H. (1997) The nitrogen dynamics of 1-, 2- and 3-year stands of alfalfa in a cropping system. *Agriculture, Ecosystems and Environment* 64, 1–10.
- Khaity, M. and Lemaire, G. (1992) Dynamics of shoot and root growth of lucerne after seeding and after cutting. *European Journal of Agronomy* 1, 36–42.
- Kragten, S., Trimbo, K.B. and de Snoo, G.R. (2008) Breeding skylarks (*Alauda arvensis*) on organic and conventional arable farms in the Netherlands. *Agriculture, Ecosystems and Environment* 126, 163–167.
- Lamb, J.F.S., Sheaffer, C.C. and Samac, D.A. (2003) Population density and harvest maturity effects on leaf and stem yield in alfalfa. *Agronomy Journal* 95, 635–641.
- Lamb, J.F.S., Jung, H.J.G., Sheaffer, C.C. and Samac, D.A. (2007) Alfalfa leaf protein and stem cell wall polysaccharide yields under hay and biomass management systems. *Crop Science* 47, 1407–1415.
- Landré, B., Bournoville, R., Aupinel, P., Carré, S., Badenhauer, I., Girousse, C. and Julier, B. (1999) Ranking of some lucerne and medics cultivars for pea aphid resistance. In: *Proceedings of the 13th Eucarpia Medicago sativa Group*, Perugia, Italy, 13–16 September 1999. University of Perugia, Perugia, Italy, pp. 231–238.
- Le Buanec, B. (1997) An overview of the world seed market. *International Herbage Seed Production Research Group Newsletter* 27, 12–15.
- Leclercq, D. and Caubel, G. (1991) Varietal resistance of lucerne to the stem nematode *Ditylenchus dipsaci* (Kuhn) Filipjev – the screening method and its application in selection for resistance. *Agronomie* 11, 603–612.
- Lemaire, G. and Allirand, J.M. (1993) Relation entre croissance et qualité de la luzerne: interaction genotype–mode d'exploitation. *Fourrages* 134, 183–198.
- Lemaire, G., Cruz, P., Gosse, G. and Chartier, M. (1985) Etude des relations entre la dynamique de prélèvement d'azote et le dynamique de croissance en matière sèche d'un peuplement de luzerne (*Medicago sativa* L.). *Agronomie* 5, 685–692.
- Lory, J.A., Russelle, M.P. and Heichel, G.H. (1992) Quantification of symbiotically fixed nitrogen in soil surrounding alfalfa roots and nodules. *Agronomy Journal* 84, 1033–1040.
- Louarn, G., Pereira-Lopès, E., Fustec, J., Mary, B., Voisin, A.S., de Faccio Carvalho, P.C. and Gastal, F. (2015) The amounts and dynamics of nitrogen transfer to grasses differ in alfalfa and white clover-based grass–legume mixtures as a result of rooting strategies and rhizodeposit quality. *Plant and Soil* 389, 289–305.
- Maamouri, A., Louarn, G., Gastal, F., Béguier, V. and Julier, B. (2015) Effects of lucerne genotype on morphology, biomass production and nitrogen content of lucerne and tall fescue in mixed pastures. *Crop and Pasture Science* 66, 192–204.
- Malik, P.K. and Singhal, K.K. (2009) Effect of lucerne (*Medicago sativa*) fodder supplementation on nutrient utilization and enteric methane emission in male buffalo calves fed on wheat straw-based total mixed ration. *Indian Journal Animal Science* 79, 416–421.
- Mauriès, M. (2003) *Luzerne Culture Récolte Conservation Utilisation*. France Agricole Ed., Paris, 240 pp.

- McCaslin, M. and Reisen, P. (2012) New technology for alfalfa. In: *California Alfalfa and Grains Symposium*, Sacramento, California, 10–12 December 2012. Available at: <http://alfalfa.ucdavis.edu> (accessed 5 November 2013).
- Molinéro-Demilly, V., Montegano, B., Julier, B., Giroult, C., Baudouin, P., Chosson, J.F., Bayle, B., Noël, D., Guénard, M. and Gensollen, V. (2007) Resistance to *Verticillium albo-atrum* in lucerne (*Medicago sativa* L.) to distinguish between varieties. *Euphytica* 153, 227–232.
- Morelli, F. (2012) Correlations between landscape features and crop type and the occurrence of the ortolan bunting *Emberiza hortulana* in farmlands of Central Italy. *Ornis Fennica* 89, 264–272.
- Mortenson, M.C., Schuman, G.E. and Ingram, L.J. (2004) Carbon sequestration in rangelands interseeded with yellow-flowering alfalfa (*Medicago sativa* ssp. *falcata*). *Environmental Management* 33, S475–S481.
- Muller, M., Poncet, C., Prosperi, J., Santoni, S. and Ronfort, J. (2006) Domestication history in the *Medicago sativa* species complex: inferences from nuclear sequence polymorphism. *Molecular Ecology* 15, 1589–1602.
- Ostrowski-Meissner, H., Ohshima, M. and Yokota, H.O. (1995) Hypocholesterolemic activity of a commercial high-protein leaf extract used as a natural source of pigments for laying hens and growing chickens. *Japanese Poultry Science* 32, 184–193.
- Pecetti, L., Romani, M., De Rosa, L. and Piano, E. (2008) Selection of grazing-tolerant lucerne cultivars. *Grass Forage Science* 63, 360–368.
- Peterson, P.R., Sheaffer, C.C. and Halla, M.H. (1992) Drought effects on perennial forage legume yield and quality. *Agronomy Journal* 84, 774–779.
- Quiros, C.F. and Bauchan, G.R. (1988) The genus *Medicago* and the origin of the *Medicago sativa* complex. In: Hanson, A.A., Barnes, D.K. and Hill, R.R. (eds) *Alfalfa and Alfalfa Improvement*. American Society of Agronomy (ASA), Crop Science Society of America (CSSA) and Soil Science Society of America (SSSA), Madison, Wisconsin, pp. 93–124.
- Rasse, D.P., Smucker, A.J.M. and Schabenberger, O. (1999) Modifications of soil nitrogen pools in response to alfalfa root systems and shoot mulch. *Agronomy Journal* 91, 471–477.
- Raynal, G., Gondran, J., Bournoville, R. and Courtillot, M. (1989) *Ennemis et Maladies des Prairies*. Institut National de la Recherche Agronomique (INRA), Paris.
- Rochette, P., Angers, D.A., Bélanger, G., Chantigny, M., Prévost, D. and Lévesque, G. (2004) Emissions of N₂O from alfalfa and soybean crops in Eastern Canada. *Soil Science Society of America Journal* 68, 493–506.
- Rollin, O., Bretagnolle, V., Decoutye, A., Aptel, J., Michel, N., Vaissière, B.E. and Henry, M. (2013) Differences of floral resource use between honey bees and wild bees in an intensive farming system. *Agriculture, Ecosystems and Environment* 179, 78–86.
- Russelle, M.P., Lamb, J.F.S., Turyk, N.B., Shaw, B.H. and Pearson, B. (2007) Managing nitrogen contaminated soils: benefits of N₂-fixing alfalfa. *Agronomy Journal* 99, 738–746.
- Salamolard, M., Butet, A., Leroux, A. and Bretagnolle, V. (2000) Responses of an avian predator to variations in prey density at a temperate latitude. *Ecology* 81, 2428–2441.
- Sinskaya, E.N. (1950) *Flora of Cultivated Plants of the USSR. XIII Perennial Leguminous Plants. Part I. Medic, Sweetclover, Fenugreek*. Jerusalem Israel Program for Scientific Translations, Jerusalem, Israel.
- Spandl, E., Kells, J.J. and Hesterman, O.B. (1999) Weed invasion in new stands of alfalfa with perennial forage grasses and an oat companion crop. *Agronomy Journal* 39, 1120–1124.
- Thiébeau, P., Larbre, D., Usunier, J., Cattin, G., Parnaudeau, V. and Justes, E. (2004) Effets d'apports de lisier de porcs sur la production d'une luzerne et la dynamique de l'azote du sol. *Fourrages* 180, 511–525.
- Thiébeau, P., Badenhauer, I., Meiss, H., Bretagnolle, V., Carrère, P., Chagué, J., Decourtye, A., Maleplate, T., Médiène, S., Lecompte, P., Plantureux, S. and Vertès, F. (2010) Contribution des légumineuses à la biodiversité des paysages ruraux. *Innovations Agronomiques* 11, 187–204.

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- Undersander, D., Cosgrove D., Cullen, E., Grau, C., Rice, M.E., Renz, M., Sheaffer, C., Shewmaker, G. and Sulc, M. (2011) *Alfalfa Management Guide*. American Society of Agronomy (ASA), Madison, Wisconsin, 59 pp.
- Vertès, F., Jeuffroy, M.H., Louarn, G., Voisin, A.S. and Justes, E. (2015) Legume use in temporary pastures: supplying nitrogen in crop-rotation systems. *Fourrages* 223, 221–232.
- Wagner-Riddle, C. and Thurtell, G.W. (1998) Nitrous oxide emissions from agricultural fields during winter and spring thaw as affected by management practices. *Nutrient Cycling in Agroecosystems* 52, 151–163.

12 Mixtures of Legumes for Forage Production

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Abstract

In Europe, legumes are mostly grown as single species or in mixtures with cereals or grasses. As an alternative cropping strategy, mixtures of legumes for forage have been developed in Serbia. This novel approach can be applied in many other temperate regions of Europe. This chapter provides an overview of these cropping systems, their use and their development. Carefully designed mixtures of forage crop species offer advantages over the component species grown separately. These advantages include higher yield, enhanced weed control and reduced soil erosion. In addition, the use of legumes in forage mixtures has benefits for feed quality due to the high protein content of the legume. This chapter examines the use of annual legumes mixed with perennial legumes to boost first-year yields in particular. Our research has shown that an annual forage legume can provide a yield benefit when sown as the companion crop during the establishment phase of a perennial legume. This research also shows that including field pea as a companion crop significantly increased overall dry matter yields and reduced weeds in red clover stands. Similar research is in progress for the establishment of lucerne (*Medicago sativa* L.) and sainfoin (*Onobrychis viciifolia* Scop.). We also examined the intercropping of annual temperate legumes with each other for forage production, and found that all mixtures out-yielded their components grown as pure stands. The evidence in the literature that explains this is reviewed.

Introduction

The cropping systems described here were developed in Serbia, where agricultural production systems range from specialized arable cropping and livestock raising in relevant regions, to traditional mixed farming systems. A combination

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of livestock raising and fruit and/or wine growing is common. The farming systems in the fertile northern areas (Vojvodina) and central parts of the country are dominated by intensive arable cropping and dairy farming. In the less fertile and predominantly mountainous regions of southern Serbia, the diverse farming systems are based on vegetables, vineyards, and forage crops to support the livestock.

Legumes are incorporated into Serbian cereal cropping systems as green manures, intercrops and rotational crops. They contribute high-quality organic matter to the soil and are effective in breaking the disease cycles of cereal crops.

Many farms in Vojvodina province have been affected by soil degradation. Inherently fertile soils such as the chernozem (black) soils have suffered a significant reduction in organic matter, in some cases as much as 50% (Ćupina *et al.*, 2011a). Farmers are trying to reverse this process by using crop rotation, and especially by including legumes that are mostly sown as a winter cover crops and are used as green manure or as forage (Fig. 12.1).

Of the 3.3 million ha of arable land in Serbia, 8% is used for forage crop production. Lucerne (alfalfa; *Medicago sativa* L.) is the most important forage crop grown on 180,000 ha. Red clover (*Trifolium pratense* L.) is grown on 80,000 ha and annual legumes on over 30,000 ha. Intercropping of annual legumes (field pea, *Pisum sativum* L. and vetches, *Vicia* spp.) and cereals (mostly oat, *Avena sativa* L.) is found typically on farms that have livestock, and the practice is particularly important on relatively small farms (Erić *et al.*, 2010).

Intercropping

Intercropping is the growing of two or more crops in the same field at the same time (Willey, 1979). Combinations of crops that do not fix nitrogen and legumes are regarded as a most effective (Corre-Hellou *et al.*, 2006). This is due to the stimulating effect of the non-legume on the biological nitrogen (N) fixation in the legume (Hauggaard-Nielsen and Jensen, 2005; Temperton *et al.*, 2007; Zarea *et al.*, 2008; Fustec *et al.*, 2010). The focus of this chapter, however, is the intercropping of legumes with legumes for forage purposes. If the components are



Fig. 12.1. Vetches and a mixture of vetches and wheat used as cover crops: cutting regime (A) and mulching regime (B). (Photo credit: B. Ćupina.)

carefully selected, intercrops of legumes have potential advantages compared with sole crops. These include: (i) increased forage yield and enhanced weed control (Avola *et al.*, 2008); (ii) decreased soil erosion (Wiersma *et al.*, 1999); and (iii) reduced incidences of pests and diseases (Trenbath, 1993; Altieri, 1999; Malézieux *et al.*, 2009). Intercropping exploits the benefits of diversity, interactions between species, and other natural regulation mechanisms (Vandermeer *et al.*, 1998) to use the available resources more efficiently than sole crops (Anil *et al.*, 1998).

Intercropping of annual and perennial crops can be applied to forage crops in Europe in four main forms (Zemenchik *et al.*, 2000; Koivisto, 2002; Thorsted *et al.*, 2002). These are as follows.

1. Two or more annual forages sown together.
2. An annual companion crop used to establish a perennial forage crop (Fig. 12.2).
3. Annual forages sown into an existing perennial stand to boost short-term yields.
4. Perennial legumes sown between the rows of an annual arable crop, such as maize.

Temperate perennial forage legumes, such as red clover, lucerne and sainfoin (*Onobrychis viciifolia* Scop.), are established either in late summer and early autumn, or in spring. Due to their small seed size, perennial legumes are sown shallow, so are especially susceptible to drought during the germination and establishment phase. A spring-sown perennial forage crop frequently has a significantly lower yield in the year of establishment in comparison to the autumn-sown one, partly because of weeds (Ćupina *et al.*, 2000, 2004). To overcome this, farmers in Europe have traditionally established perennial forage crops using a companion crop (Klesnil, 1980; Matejkova, 1982; Tesar and Marble, 1988; Zollinger and Meyer, 1996), often a cereal, such as oat. This practice usually increases the total forage yield, enhances the forage quality and reduces the weed invasion (Fig. 12.3) (Vandermeer *et al.*, 1998). Nevertheless, using a companion crop in the establishment of a perennial forage legume has its limitations, since the annual companion species may also compete to the detriment of the perennial (Tesar and Marble, 1988), especially where oat or another cereal is used. For this

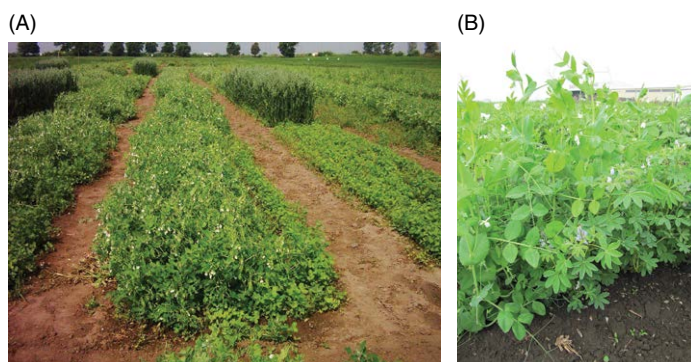


Fig. 12.2. Two approaches to intercropping legumes. (A) Field pea used as a nurse crop for red clover. (B) A mixture of white lupin and field pea. (Photo credits: Đ. Krstić (A) and S. Vujić (B).)

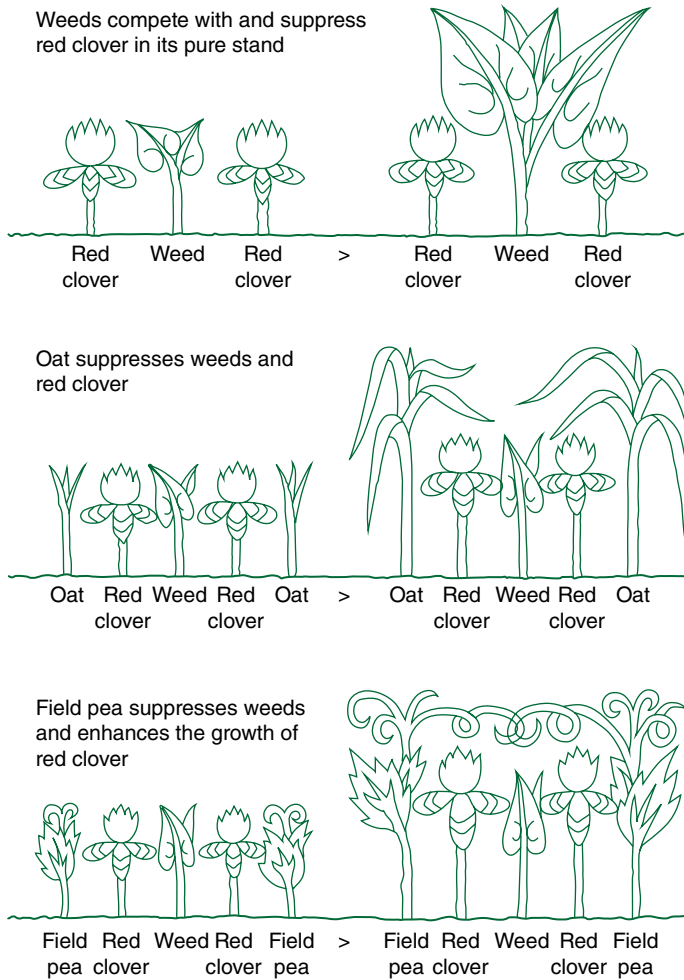


Fig. 12.3. Different ways of using nurse crops in the establishment of perennial legumes with their effects. (From Čupina *et al.*, 2011d.)

reason, an alternative and economically reliable scheme has been suggested, where an annual legume, such as pea, is used (Fig. 12.3).

The success of using an annual companion crop in establishing a perennial forage legume depends on the capacity of the perennial to develop in the shade of the annual (Tan *et al.*, 2004). Competition for light has a direct impact on the morphology and physiology of the perennial species that lies lower in the canopy (Bedoussac and Justes, 2010).

Our research has focused on using pea as a companion species in particular. The light intensity at the level of the perennial forage legume under the pea companion crop is consistently higher compared with that under other companion crops that have a more robust growth habit (Simmons *et al.*, 1995). Semi-leafless (afila) pea cultivars in particular increase the total capture of photosynthetically

active radiation (PAR), so they are considered to be more appropriate for intercropping (Heath and Hebblethwaite, 1985).

Developing and Managing Mixtures of Legumes – the Fundamentals

Optimizing the growth of a mixture of perennial and annual forage species depends on finely balancing the benefits of the additional biomass and weed control provided by the annual with the negative effects of shading on the perennial. To achieve this, an understanding of the physiological responses within the stand is useful.

It is well established that leaves adapt to the light environment. Anatomical variation induced by the light environment has consequences for photosynthesis, as better development of palisade tissue in sun leaves gives a high photosynthetic capacity (Dickison, 2000). Leaves grown in the shade have lower photosynthetic saturation points than those developed in full sun (Björkman, 1981; Taiz and Zeiger, 2002). This fundamental effect provides the basis for the benefits of intercropping, enabling shaded plants to survive shading and respond positively through new leaf development when the shading companion crop is removed.

This general effect of shading on photosynthetic responses can be observed in specific intercrops. In a red clover or lucerne–pea mixture, reduced light intensity retards the growth and leaf area development of the clover (Heichel *et al.*, 1988). This effect increases as the number of pea plants of either leafy or semi-leafless cultivars above the clover or lucerne increases (Krstić *et al.*, 2005a, b). The leaves and other plant parts receiving only diffuse light often have a higher chlorophyll content than those exposed to direct light. Thus, the contents of both chlorophyll a and b were lower in the sole crops of lucerne (10 mg/g) and red clover (12 mg/g) than in their intercrops with field pea (18 mg/g). This increased chlorophyll concentration enables the perennial crop to benefit from the protection of the pea while still establishing effectively in shade. Furthermore, we have observed that differences in plant architecture and morphology of the intercropped field pea cultivars did not induce significant differences in lucerne leaf anatomical parameters (Zorić *et al.*, 2012).

The overall effect is that establishing lucerne or red clover with a companion crop of field pea increases the total capture of solar radiation, increasing overall crop yields.

It is noteworthy that most of the perennial plant rosette remains after the first cut of a perennial forage legume. This part enables the plant to recover faster than the covering nurse crop (Krstić *et al.*, 2005b). This means that harvesting favours the perennial over the annual, further reinforcing the benefits of this type of intercropping.

The results of our research in the conditions of Serbia confirm that lucerne, from both anatomical and morphological aspects, may be successfully established and cultivated with a companion crop of field pea, regardless of its leaf type, in an environment-friendly way, thus providing various farming systems with reliable ecological services (Zorić *et al.*, 2012).

Optimizing Interspecific Interactions when Establishing Perennial Forage Crops

Effect of pea cultivar

Careful selection of the companion pea cultivar is important in optimizing pea–perennial crop mixtures in some circumstances. Leafy field pea cultivars are susceptible to lodging, so they introduce a high risk of suppressing the growth of the undersown perennial forage crop to the detriment of the overall crop yield (Faulkner, 1985; Gilliland and Johnston, 1992). However, in a 3-year field study carried out in Serbia (Čupina *et al.*, 2010b), two pea cultivars with different leaf types, namely leafy cv. ‘Javor’ and semi-leafless cv. ‘Jezero’, did not differ significantly as cover for red clover. The crops also had similar forage yields, with no consistent differences in 2 establishment years, confirming the previous results (Koivisto, 2002).

Optimizing plant populations

Using the optimum seed rate for the nurse (cover) species is central to establishing the optimum balance with perennial crop (Tan *et al.*, 2004). A high population of the companion crop increases first-year forage yields and suppresses weeds, but can adversely affect the longer-term potential of the perennial crop. Lower companion seed rates may not be sufficient to suppress weeds, but provide the intercrop canopy with more solar radiation and better air movement (Tesar and Marble, 1988; Horrocks and Vallentine, 1999). Given these trade-offs, it is recommended that the seeding rate of the companion crop (in viable seeds/m²) should not exceed half of the seeding rate of the perennial crop.

Early first cutting reduces competition from the cover crop. In the case of using peas, this means cutting at the early pod-filling stage (Vough *et al.*, 1995).

Čupina *et al.* (2010b) reported that the highest annual forage dry matter yield (7.66 t/ha) and the lowest weed cover in the first cut of the newly established red clover (5.9%) were obtained where clover was mixed with the highest sowing rate of field pea tested (90 plants/m²) (Fig. 12.4). From an economic perspective, a lower pea plant population of 60 plants/m² may be more appropriate. In the same experiment, the highest forage yields in the first year were obtained from red clover intercropped with oat. However, forage digestibility in ruminants is an important parameter which in these conditions ranges from 70% to 80% in field pea and 50–60% in oat (Smith *et al.*, 1972; Obračević, 1990). Additionally, field pea has morphological and biological characteristics that make it more suitable than oat for use as a companion crop for red clover in both the establishment and the first full harvest years. In the second and subsequent years, perennial legumes that were grown with pea had a better regeneration rate and thus higher total annual yield.

By contributing to the forage yield in the first cut, the annual companion crop contributes to the average annual forage yield. Generally, the use of an annual

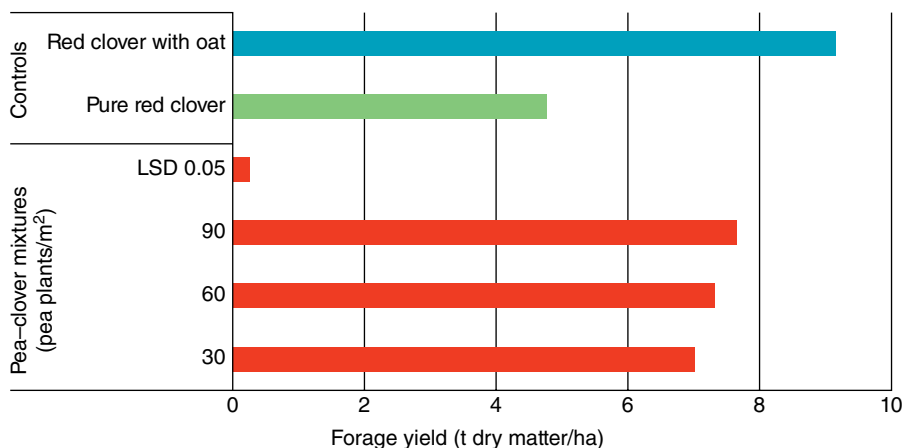


Fig. 12.4. Forage yields of red clover and mixtures of red clover with oats and pea. The three pea–clover mixtures with different pea plant populations (sowing rate of 30 pea plants/m², 60 plants/m² and 90 plants/m²) are compared with a pure stand of red clover and red clover mixed with oat. LSD, Least significant difference. (From Čupina *et al.*, 2010c.)

legume as a companion crop instead of oat results in a lower proportion of the first-year yield coming from the first cut. On average, the proportion of the first cut in the annual yield may range from 50% to about 70% where pea is the companion crop, which is similar to the proportion of first cuts in pure stands. In comparison, where oat is used, a larger proportion of the first-year forage yield is in the first cut. The first-cut yield of lucerne intercropped with oat in the establishment year may comprise between 70% and nearly 100% of the total first-year yield. The reason is that oat intercropped with a perennial forage legume often reduces the forage yields in subsequent cuts during the establishment year (Lanini *et al.*, 1991).

Mixtures of Annual Legumes

Compared with the intercropping of legumes with cereals, grasses and brassicas, reports of the intercropping of annual legumes species are rare. White lupin (*Lupinus albus* L.) used phosphorus more effectively when intercropped with soybean (*Glycine max* L.) than on its own (Braum and Helmke, 1995). Similarly, intercropping soybean and pigeon pea (*Cajanus cajan* L.) may mitigate the effects of an unpredictable drought (Ghosh *et al.*, 2006a). Annual legume species rich in bioactive compounds, such as fenugreek (*Trigonella foenum-graecum* L.), are efficient in reducing the infection of faba bean by broomrape (*Orobanche crenata* Forssk.) (Evidente *et al.*, 2007; Fernández-Aparicio *et al.*, 2011). However, intercropping annual legumes with each other may cause undesirable effects, such as competition for nutrients that may reduce the growth of one legume, as in the case of intercropping pigeon pea with soybean, due to nitrogen deficiency (Ghosh *et al.*, 2006b).

We have developed the intercropping of annual legumes for both forage and grain production (Ćupina *et al.*, 2011c). This began with an evaluation of several hundred accessions of numerous cool- and warm-season annual legume species of diverse geographic and genetic origin and status in the collection maintained in Novi Sad. The goal was to assess the potential of components in various two-way combinations as intercrops for forage and grain production (Antanasović *et al.*, 2011). The main conclusions of this research are illustrated in Fig. 12.5.

Annual legumes such as vetches with lodging stems suppress weeds, but forage yields are low because of the degradation of lower leaves. In contrast, faba bean (*Vicia faba* L.) is susceptible to weed infestation as a sole crop. Mixing these combines the good standing ability of the faba bean with weed suppression from the vetch. Intercropping using an incompatible mixture reduces yield by giving

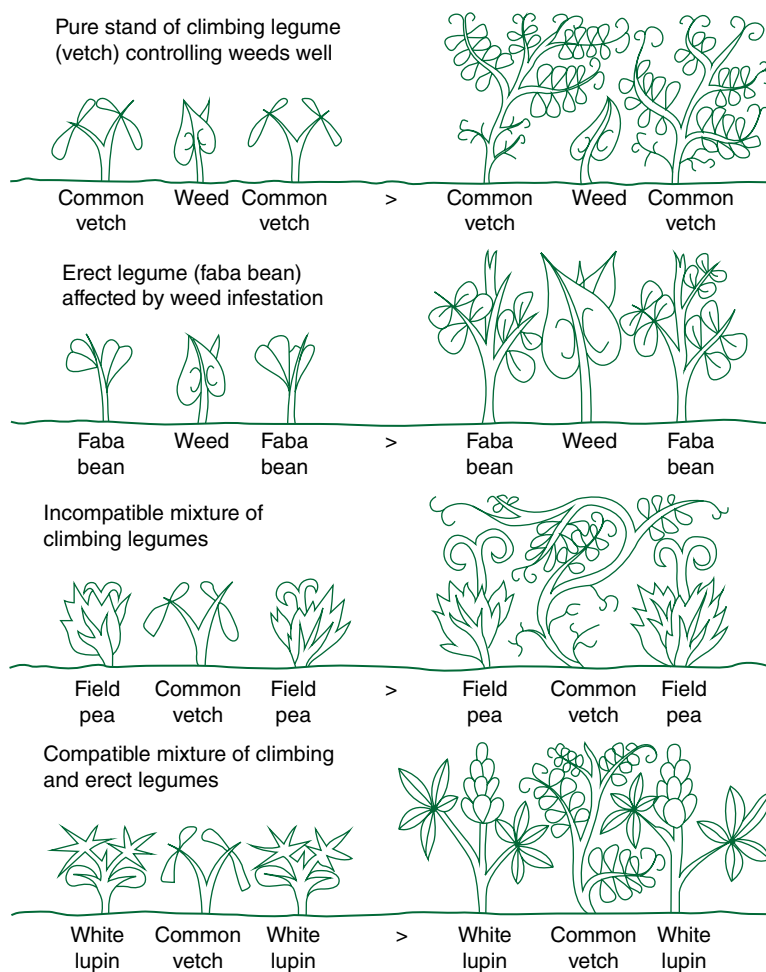


Fig. 12.5. Different approaches to intercropping annual legumes with each other. (From Ćupina *et al.*, 2011d.)

advantage to one component, such as common vetch (*Vicia sativa* L.), while severely affecting another one, such as semi-leafless pea. A compatible, functional and reliable intercropping is one such as white lupin and common vetch, providing the best possible conditions and effects.

On the basis of the results of our experiments and wider knowledge, we have established four basic requirements for a successful intercropping of two annual legume species for forage production (Ćupina *et al.*, 2011d).

1. Components should have the same optimum sowing time.
2. Components should have similar heights.
3. Components should have similar full flowering times to achieve a balance between forage yield and its quality.
4. One component needs to have a good standing ability (supporting crop) to complement the component that is more susceptible to lodging.

Annual Legume Forage Intercrops for Farm Use

From these requirements, we have examined the performance of three main groups of the annual legume intercrops that are expected to over-yield (Mikić *et al.*, 2012):

- autumn- and spring-sown 'tall' cool-season annuals;
- autumn- and spring-sown 'short' cool-season annuals; and
- early and late maturing warm-season annuals.

Each component of the two-way mixtures was included at 50% of its pure-stand seeding rate.

'Tall' cool-season annuals

For our autumn sowings, faba bean was the supporting crop, while forage pea, common vetch, Hungarian vetch (*Vicia pannonica* Crantz) and hairy vetch (*Vicia villosa* Roth) were the supported crops (Fig. 12.6). For spring sowing, faba bean and white lupin were the supporting crops, while forage pea, common vetch and grass pea (*Lathyrus sativus* L.) were the supported crops.

The performance of an intercrop is expressed using the land equivalent ratio (LER). This is the yield of the intercrop compared with the yield of the components grown separately on the same area of land, expressed as a ratio. An LER of 1.1 means that the intercrop had a 10% higher yield than the total of the components grown separately. Intercropping autumn-sown faba bean with common vetch proved especially effective with both contributing similarly to the total forage dry matter yield and an LER of 1.42 (Ćupina *et al.*, 2011d). These experiments also evaluated a range of seeding-rate relationships: 50%/50%, 75%/25% and 25%/75%. The intercrops of 50% faba bean with 50% of grass pea, and 75% white lupin with 25% grass pea had the best agronomic performance, with LERs for green forage yield of 1.44 and 1.21, respectively (Ćupina *et al.*, 2009). The



Fig. 12.6. Examples of intercropping 'tall' cool-season legumes: (A) autumn sowing – white lupin with common vetch; (B) spring sowing – faba bean with common vetch. (From Mikić *et al.*, 2012.)

intercrops of white lupin with common vetch resulted in high values of LER for green forage yield in all three ratios, averaging 1.28 (Čupina *et al.*, 2011b).

'Short' cool-season annuals

'Short' cool-season annual forage legumes have short stems with fewer nodes, often determinate stem growth and more uniform stages of growth and development. In our experiments, the autumn-sown option comprised semi-leafless pea as the supporting crop and leafy pea and bitter vetch (*Vicia ervilia* (L.) Willd.) as the supported crop. The spring-sown option was leafy pea with lentil (*Lens culinaris* Medik.) serving as the supported crop.

Semi-leafless pea allows good light penetration into the stand, providing favourable conditions for weed growth, which is countered by the presence of the companion. Mixing these two types of pea increased forage yield (Table 12.1) (Čupina *et al.*, 2010a). The intercrops of autumn-sown semi-leafless pea with bitter vetch had an LER for forage dry matter yield of only 0.91, whereas that of spring-sown semi-leafless pea with lentil had an LER for forage dry matter yield of 1.09 (Mikić *et al.*, 2012).

Warm-season annuals

Warm-season annual forage legumes are sown in late spring. In our trials, early- and late-maturing mixtures were tested. In the early-maturing group, soybean belonging to the 00 maturity group was the supporting crop, while several *Vigna* species, namely mung bean (*Vigna radiata* L.), adzuki bean (*Vigna angularis* (Willd.) Ohwi & Osashi) and black gram (*Vigna mungo* L.) were the supported crops. Within the late-maturing group, soybean belonging to a late-maturity group and pigeon pea served as supporting crops, while cowpea (*Vigna unguiculata* (L.) and hyacinth bean (*Lablab purpureus* (L.) were the supported crops (Mikić *et al.*, 2012).

Table 12.1. Forage dry matter yields (t/ha) and corresponding land equivalent ratios (LER) in intercrops of pea cultivars with different leaf types at Rimski Šančevi during 2008–2010. (From Čupina *et al.*, 2010a.)

Season	Treatment	Forage dry matter yield (t/ha)			LER for forage dry matter
		Supporting component	Supported component	Total	
Winter	'Dove', pure stand	6.8	0.0	6.8	1.00
	'Frijaune', pure stand	0.0	7.8	7.8	1.00
	'Dove' + 'Frijaune'	5.1	3.0	8.1	1.13
Spring	'Jezero', pure stand	6.3	0.0	6.3	1.00
	'Javor', pure stand	0.0	6.4	6.4	1.00
	'Jezero' + 'Javor'	2.9	3.6	6.5	1.03
LSD _{0.01} ^a			0.8		0.08

^aLSD, Least significant difference.

A schematic of the responses in these mixtures is depicted in Fig. 12.7. Regardless of its maturity group, a soybean crop provides favourable conditions for weed development and thus regularly requires intensive weed control measures. In contrast, cowpea and hyacinth bean are notoriously prone to lodging. Both develop a mass of creeping cover able to counter weed species but these may suffer losses of lower biomass and may be difficult to harvest due to lodging. When intercropped, soybean carries the cowpea or lablab plants preserving their protein-rich leaves combined with a significant benefit from essentially reduced weed infestation.

In the preliminary trials with intercrops of warm-season annual forage legumes carried out at Rimski Šančevi and Zemun Polje near Belgrade, almost all proved as economically reliable and superior to the pure stands (Mikić *et al.*, 2010). Intercropping pigeon pea with hyacinth bean performed particularly well, with an LER for forage dry matter yield of 1.10. Additional data indicate that the performance of the intercrops of soybean belonging to the 00 maturity group with adzuki bean and black gram were better than the one with mung bean, with an LER for forage dry matter yield of 1.07 and 1.11, respectively (Mikić *et al.*, 2012).

Conclusions

An annual legume used as the companion crop in the establishment of the perennial forage crop can increase total forage yields. The superiority of intercropping over pure stands is attributed generally to variations between species in morphological characteristics resulting in more efficient capture of resources. In addition, field pea as a companion crop contributes to improving forage quality and digestibility.

We conclude that legumes can be intercropped together successfully. It is emphasized that such intercrops do not increase the costs of crop establishment.

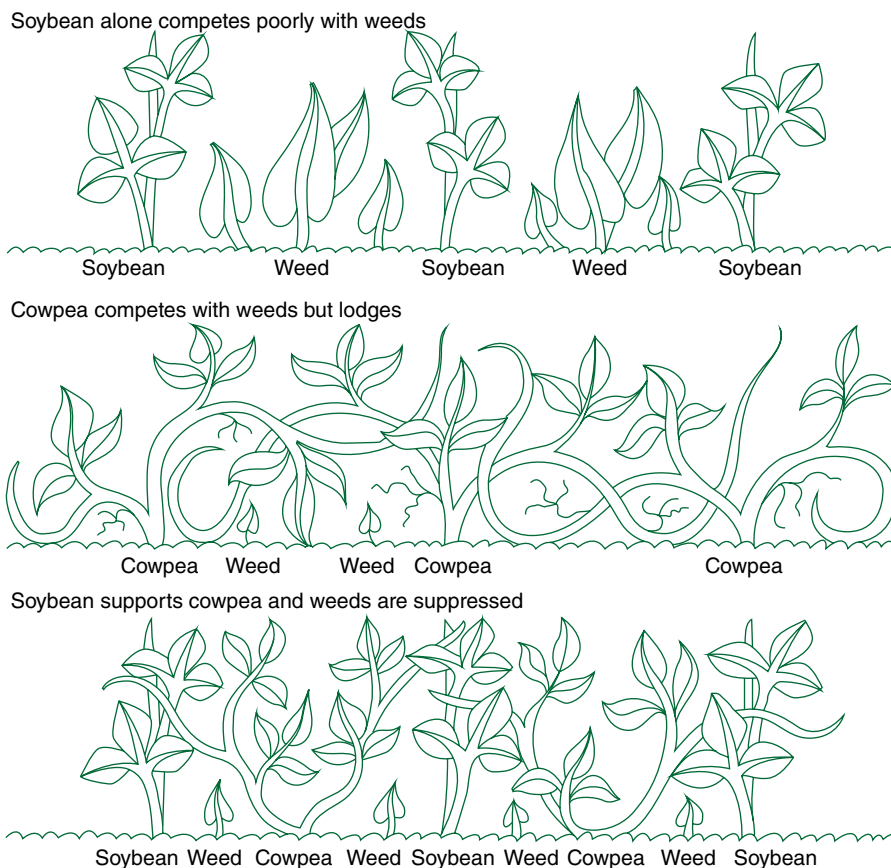


Fig. 12.7. Model of intercropping warm-season legumes. (From Mikić *et al.*, 2012.)

At the same time, when both components in an intercrop are legumes, the crude protein content in forage dry matter remains high and does not decrease as happens in the case of intercropping with cereals. All three presented models of annual forage legume intercrops are characterized by short growing seasons and thus are able to fit easily into various cropping systems. Producing forage in such intercrops does not require the application of either synthetic nitrogen fertilizer, since both components are legumes, or herbicides, due to an enhanced weed control, and thus confirms its value as a true environment-friendly service.

There remain questions to address including: (i) the optimum ratios for individual intercrops; (ii) the impact of intercropping on forage yield components; (iii) possible correlations between total forage yields and their LER values; (iv) the chemical composition of the forage dry matter in the intercrop components; and (v) various underground aspects, with particular regard to microbiology and allelopathy. Reliable seed production of the intercropping-specific annual forage legume cultivars is also required in order to secure their successful use in general production.

Acknowledgements

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References

- Altieri, M. (1999) The ecological role of biodiversity in agroecosystems. *Agricultural Ecosystems and Environment* 74, 19–31.
- Anil, L., Park, J., Phipps, R.H. and Miller, F.A. (1998) Temperate intercropping of cereals for forage: review of the potential for growth and utilisation with particular reference to the UK. *Grass and Forage Science* 53, 301–317.
- Antanasović, S., Mikić, A., Čupina, B., Krstić, Đ., Mihailović, V., Erić, P. and Milošević, B. (2011) Some agronomic aspects of the intercrops of semi-leafless and normal-leafed dry pea cultivars. *Pisum Genetics* 43, 25–28.
- Avola, G., Tuttbene, R., Gresta, F. and Abbate, V. (2008) Weed control strategies for grain legumes. *Agronomy and Sustainable Development* 28, 389–395.
- Bedoussac, L. and Justes, E. (2010) Dynamic analysis of competition and complementarity for light and N use to understand the yield and the protein content of a durum wheat–winter pea intercrop. *Plant Soil* 330, 37–54.
- Björkman, O. (1981) Responses to different quantum flux densities. In: Lange, O.L., Nobel, P.S., Osmond, C.B. and Zeigler, H. (eds) *Encyclopedia of Plant Physiology*. New Series. Springer, Berlin, pp. 57–107.
- Braun, S.M. and Helmke, P.A. (1995) White lupin utilizes soil phosphorus that is unavailable to soybean. *Plant Soil* 176, 95–100.
- Corre-Hellou, G., Fustec, J. and Crozat, Y. (2006) Interspecific competition for soil N and its interaction with N₂ fixation, leaf expansion and crop growth in pea–barley intercrops. *Plant Soil* 282, 195–208.
- Čupina, B., Mihailović, V. and Erić, P. (2000) Management practices for yield and quality of field pea. *Ratarstvo i povrtarstvo* 33, 91–102.
- Čupina, B., Erić, P., Mihailović, V. and Mikić, A. (2004) The role and importance of cover crops in sustainable agriculture. *Ratarstvo i povrtarstvo* 40, 419–430.
- Čupina, B., Mikić, A., Mihailović, V., Krstić, Đ. and Đurić, B. (2009) Intercropping of grass pea (*Lathyrus sativus*) with other grain legumes for forage production. *Grain Legume* 54, 32.
- Čupina, B., Krstić, Đ., Antanasović, S., Erić, P., Pejić, B., Mikić, A. and Mihailović, V. (2010a) Potential of the intercrops of normal-leafed and semi-leafless pea cultivars for forage production. *Pisum Genetics* 42, 11–14.
- Čupina, B., Krstić, Đ., Mikić, A., Erić, P., Vučković, S. and Pejić, B. (2010b) Field pea companion crop management on red clover establishment and productivity. *Turkish Journal of Agriculture and Forestry* 34, 275–283.
- Čupina, B., Manojlović, M., Krstić, D., Čobilovski, R., Mikić, A., Ignjatović-Čupina, A. and Erić, P. (2011a) Effect of winter cover crops on the dynamics of soil mineral nitrogen and yield and quality of Sudan grass (*Sorghum bicolor* (L.) Moench). *Australian Journal of Crop Science* 5(7), 839–845.

- Čupina, B., Mikić, A., Krstić, Đ., Antanasović, S., Erić, P., Đorđević, V. and Perić, V. (2011b) Intercropping white lupin with other annual legumes for forage and grain production. In: Book of Abstracts for the 13th International Lupin Conference, Poznań, Poland, 6–10 June 2011, 25.
- Čupina, B., Mikić, A., Krstić, Đ., Antanasović, S., Pejić, B., Erić, P. and Ignjatović-Čupina, A. (2011c) Mutual intercropping of spring annual legumes for grain production in the Balkans. *Indian Journal of Agricultural Science* 81, 971–972.
- Čupina, B., Mikić, A., Stoddard, F.L., Krstić, Đ., Justes, E., Bedoussac, L., Fustec, J. and Pejić, B. (2011d) Mutual legume intercropping for forage production in temperate regions. In: Lichtfouse, E. (ed.) *Sustainable Agriculture Reviews 7. Genetics, Biofuels and Local Farming Systems*. Springer Science+Business Media, Dordrecht, the Netherlands, pp. 347–365.
- Dickison, W.C. (2000) *Integrative Plant Anatomy*. Academic Press, San Diego.
- Erić, P., Čupina, B. and Stevović, V. (2010) Forage crops production on arable land in Serbia. *Biotechnology in Animal Husbandry* 26 (special issue 1), 173–189.
- Evidente, A., Fernández-Aparicio, M., Andolfi, A., Rubiales, D. and Motta, A. (2007) Trigoxazonane, a monosubstituted trioxazonane from *Trigonella foenum-graecum* root exudate, inhibits *Orobanche crenata* seed germination. *Phytochemistry* 68, 2487–2492.
- Faulkner, J.S. (1985) A comparison of faba beans and peas as whole-crop forages. *Grass Forage Science* 40, 161–169.
- Fernández-Aparicio, M., Emeran, A.A. and Rubiales, D. (2011) Inter-cropping faba bean with berseem, fenugreek or oat can contribute to broomrape management. *Grain Legume* 56, 31.
- Fustec, J., Lesuffleur, F., Mahieu, S. and Cliquet, J.B. (2010) N rhizodeposition of legumes. A review. *Agronomy for Sustainable Development* 30, 57–66.
- Gilliland, T.J. and Johnston, J. (1992) Barley/pea mixtures as cover crops for grass reseed. *Grass and Forage Science* 47, 1–7.
- Ghosh, P.K., Mohanty, M., Bandyopadhyay, K.K., Painuli, D.K. and Misra, A.K. (2006a) Growth, competition, yield advantage and economics in soybean/pigeonpea intercropping system in semi-arid tropics of India: I. Effect of subsoiling. *Field Crop Research* 96, 80–89.
- Ghosh, P.K., Mohanty, M., Bandyopadhyay, K.K., Painuli, D.K. and Misra, A.K. (2006b) Growth, competition, yields advantage and economics in soybean/pigeonpea intercropping system in semi-arid tropics of India: II. Effect of nutrient management. *Field Crop Research* 96, 90–97.
- Hauggaard-Nielsen, H. and Jensen, E.S. (2005) Facilitative root interactions in intercrops. *Plant Soil* 274, 237–250.
- Heath, M.C. and Hebblethwaite, P.D. (1985) Solar radiation interception by leafless, semi-leafless and leafed peas (*Pisum sativum* L.) under contrasting field conditions. *Annals of Applied Biology* 7, 309–318.
- Heichel, G.H., Delaney, R.H. and Cralle, H.T. (1988) Carbon assimilation, partitioning and utilization. In: Hanson, A.A., Barnes, D.K. and Hill, R.R. (eds) *Alfalfa and Alfalfa Improvement*. American Society of Agronomy, Madison, Wisconsin, pp. 195–228.
- Horrocks, R.D. and Vallentine, J.F. (1999) Establishment of forage species. In: Horrocks, R.D. and Vallentine, J.F. (eds) *Harvested Forages*. Academic Press, London, pp. 135–154.
- Klesnil, J. (1980) Contribution to the problem of establishing of clover crop stands. *Rostlinná výroba* 26, 6–10.
- Koivisto, J.M. (2002) Semi-leafless pea: a cover crop for establishing lucerne or red clover. PhD thesis, Royal Agricultural College, Cirencester and Coventry University, Coventry, UK.
- Krstić, Đ., Čupina, B., Erić, P. and Mihailović, V. (2005a) Fodder pea as companion crop in alfalfa establishment – effect on alfalfa morphological and physiological parameters. In: XXXV European Society for New Methods in Agriculture (ESNA) Annual Meeting, Amiens, France, 29 August–2 September 2005. ESNA, Amiens, France, pp. 40–41.

- Krstic, Đ., Čupina, B., Erić, P. and Mihailović, V. (2005b) Fodder pea as companion crop in red clover establishment – effects on red clover morphological and physiological parameters. In: Book of Abstracts for the XVI Symposium of the Society of Plant Physiology of Srbija i Crna Gora (SCG), Bajina Bašta, Serbia, 13–16 June 2005, 11.
- Lanini, W.T., Orlof, S.B., Vargas, R.N., Orr, J.P., Marable, V.L. and Grattan, S.R. (1991) Oat companion crop seeding rate effect on alfalfa establishment, yield and weed control. *Agronomy Journal* 83, 330–333.
- Malézieux, E., Crozat, Y., Dupraz, C., Laurans, M., Makowski, D. and Ozier-Lafontaine, H. (2009) Mixing plant species in cropping systems: concepts, tools and models. A review. *Agronomy for Sustainable Development* 29, 43–62.
- Matejkova, O. (1982) Limited ways of the soil cultivation to summer sowing of alfalfa. *Rostlinná výroba* 28, 233–248.
- Mikić, A., Đorđević, V., Perić, V., Čupina, B., Mihailović, V., Srebrić, M. and Krstić, Đ. (2010) Preliminary report on forage yields in mid- to late spring-sown annual legume intercrops. *Biotechnology and Animal Husbandry* 26 (special issue 2), 269–275.
- Mikić, A., Čupina, B., Mihailović, V., Krstić, Đ., Đorđević, V., Perić, V., Srebrić, M., Antanasović, S., Marjanović-Jeromela, A. and Kobiljski, B. (2012) Forage legume intercropping in temperate regions: models and ideotypes. In: Lichtfouse, E. (ed.) *Sustainable Agriculture Reviews 11*. Springer Science+Business Media, Dordrecht, the Netherlands, pp. 161–182.
- Obračević, Č. (1990) *Tablice Hranljivih Vrednosti Stočnih Hraniva i Normativa u Ishrani Preživara*. Naučna knjiga, Belgrade, Serbia.
- Simmons, S.R., Craig, S., Sheffer, D.C., Rasmussen, D.D., Stuthman, S. and Nickel, E. (1995) Alfalfa establishment with barley and oat companion crops differing in stature. *Agronomy Journal* 87, 268–272.
- Smith, L.W., Goering, H.K. and Gordon, C.H. (1972) Relationships of forage compositions with rates of cell wall digestion and indigestibility of cell walls. *Journal of Dairy Science* 55, 1140–1147.
- Taiz, L. and Zeiger, E. (2002) *Plant Physiology*, 3rd edn. Sinauer Associates, Sunderland, Massachusetts.
- Tan, M., Serin, Y. and Erkovan, H.I. (2004) Effect of barley as companion crop on the hay yield and plant density of red clover and botanical composition of hay. *Turkish Journal of Agriculture and Forestry* 28, 35–41.
- Temperton, V.M., Mwangi, P.N., Scherer-Lorenzen, M., Schmid, B. and Buchmann, N. (2007) Positive interactions between nitrogen-fixing legumes and four different neighbouring species in a biodiversity experiment. *Oecologia* 151, 190–205.
- Tesar, M.B. and Marble, V.L. (1988) Alfalfa establishment. In: Hanson, A.A., Barnes, D.K. and Hill, R.R. (eds) *Alfalfa and Alfalfa Improvement*. American Society of Agronomy (ASA), Crop Science Society of America (CSSA), Soil Science Society of America (SSSA), Madison, Wisconsin, pp. 303–332.
- Thorsted, M.D., Søegaard, K. and Koefoed, N. (2002) Yield and quality of oat/white clover intercrops. *Grassland Science in Europe* 7, 94–95.
- Trenbath, B.R. (1993) Intercropping for the management of pests and diseases. *Field Crop Research* 34, 381–405.
- Vandermeer, J., Van Noordwijk, M., Anderson, J., Ong, C. and Perfecto, I. (1998) Global change and multi-species ecosystems: concepts and issues. *Agricultural Ecosystem and Environment* 67, 1–22.
- Vough, L.R., Decker, A.M. and Taylor, T.H. (1995) Forage establishment and renovation. In: Barnes, R.F., Miller, D.A. and Nelson, J. (eds) *The Science of Grassland Agriculture*. Iowa State University Press, Ames, Iowa, pp. 29–43.
- Wiersma, D.W., Hoffman, P.C. and Mlynarek, M.J. (1999) Companion crops for legume establishment: forage yield, quality, and establishment success. *Journal of Production Agriculture* 12, 116–122.

- Willey, R. (1979) Intercropping – its importance and research needs. 1. Competition and yield advantages. *Field Crop Abstracts* 32, 1–10.
- Zarea, M.J., Ghalavand, A. and Jamshidi, E. (2008) Role of forage legumes mixed cropping on biomass yield and bacterial community composition. In: *Proceedings of the Second Scientific Conference of the International Society of Organic Agriculture Research*, Modena, Italy, 18–20 June 2008. International Society of Organic Agriculture Research, Modena, Italy, pp. 180–183.
- Zemenchik, R.A., Albrecht, K.A., Boerboom, C.M. and Lauer, J. (2000) Corn production with kura clover as a living mulch. *Agronomy Journal* 92, 698–705.
- Zollinger, R.K. and Meyer, D.V. (1996) Imazethapyr for weed control in alfalfa establishment. *Weed Science* 49, 19–21.
- Zorić, L., Krstić, Đ., Čupina, B., Mikić, A., Antanasović, S., Luković, J. and Merkulov, Lj. (2012) The effect of field pea (*Pisum sativum* L.) as companion crop on leaf histological parameters of lucerne (*Medicago sativa* L.). *Australian Journal of Crop Science* 6, 430–435.

13

Introducing Legumes into European Cropping Systems: Farm-level Economic Effects

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Abstract

Legume cultivation in Europe has declined in recent decades due to decreased farm-level economic competitiveness compared with cereal and oil crop production. The increase in soybean prices in recent years and the public benefits expected from diversified production systems are reasons to reconsider legumes in Europe. Farm-level economic assessments, based on gross margin analysis of individual crops, often underestimate the contribution that legumes make to the farm business. We addressed this deficit using assessments made at the crop rotation level. We explored the possibilities resulting from: (i) the consideration of the management and yield of subsequent crops; (ii) systematic cropping system design; and (iii) changed price relations for legume feed grain. We identified several situations where legume-supported crop rotations are competitive and can create economic and environmental win-win situations to support a sustainable intensification of European cropping systems.

Introduction

Legume production can protect and enhance public goods, including through reduced greenhouse gas and nutrient emissions, increased crop and associated biodiversity, and reduced resource requirements of cropping and animal feeding systems. In spite of these, the area cultivated with legumes has declined in recent decades (Bues *et al.*, 2013). A combination of drivers, including yield developments, public policy decisions and economic under-evaluation of the farm-level economic effects, has led European farming to specialize in cereal and oil crop production (Zander *et al.*, 2016).

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The current situation of legumes in Europe – main drivers

In Europe, the relative and absolute difference in grain yield between legumes and cereals is high (Bues *et al.*, 2013). Consequently, European farmers specialize in cereal production. Soy is imported to supplement these cereals in livestock feeds.

Furthermore, grain legume yields fluctuate more than most cereals (Cernay *et al.*, 2015). The gross margins of pea and faba bean were more volatile than those of other crop types in three out of five case study sites across Europe (LMC International, 2009). Consequently, cereals occupy on average 54% of arable land in the European Union (EU) (average 2005–2011) compared with 35% in the USA and Canada (FAOSTAT, 2014).

Legumes also compete with other broadleaved crops, especially oilseeds, even though many oil crops have similarly low and unstable yields. The high demand for these oilseed crops is partly attributable to European bioenergy policy, which has strongly favoured the production of rapeseed in particular (Robles, 2011; Peri and Baldi, 2013). Rapeseed production expanded partly at the expense of legumes (Brisson *et al.*, 2010). Since oil is a higher value component than starch (De Visser *et al.*, 2014) and the residues of oil extraction also provide a protein-rich feedstuff, expanding rapeseed production reduces the demand for legumes on the feed market as well as the amount of land available for legumes.

Underestimation of the on-farm economic impacts of diversification in cropping

Simplified farm management, maximized utilization of machinery and established value chains enable higher financial gains from cereal-based systems. However, the resulting specialization comes at the cost of increased fertilizer and pesticide requirements. Crop diversification through legumes reduces the dependency on these external inputs and often increases the yield and cost-efficiency of subsequent crops (Kirkegaard *et al.*, 2008; Peoples *et al.*, 2009a). These 'pre-crop effects' include the provision of nitrogen derived from biological nitrogen fixation to the subsequent crops (see e.g. Peoples *et al.*, 2009b, or Reckling *et al.*, 2014a) and the phytosanitary impact of breaking a sequence of similar crops (typically cereals) reduce disease, weed and pest risks (Robson *et al.*, 2002). Longer and more diverse rotations prevent the build-up of pathogens, particularly soil-borne root diseases such as take-all in cereals and clubroot in rapeseed. Legumes also have the potential to improve the structure and other quality parameters of soils (Leithold *et al.*, 1997; Jensen and Hauggaard-Nielsen, 2003; Peoples *et al.*, 2009b; Jensen *et al.*, 2011).

Approach

A combination of agroeconomic drivers (yield developments) and public policy has thus led to a focus on cereal and oil crop production in Europe. However, as

the price of soy imports and the relevance of diversification increase, the economic drivers behind specialization weaken. Our analysis is focused at the farm level, where decisions about growing legumes are taken. We therefore discuss the relevance of different economic indicators using literature and case studies, and illustrate trade-offs between economic and environmental performance and the potential to raise the on-farm economic value of legume grain through on-farm use or niche marketing.

Limitations of economic indicators

A classical and simple indicator of the economic competitiveness of a certain crop is the gross margin, calculated by deducting all variable costs from the revenues received. It is suitable for comparing crops that have similar fixed cost frameworks, such as machinery, buildings and management. It can be useful for comparing wheat and barley, for example, to help farmers decide which is the more profitable cereal to grow. In contrast, comparing cereals with tomatoes using gross margins would not be a good decision basis, because tomatoes require a completely different fixed cost base. In the case of legumes, a realistic assessment of the competitiveness of legumes requires consideration of the economic value of pre-crop effects. Hence the level of comparison needs to be raised to the level of the cropping sequence or even to the farm level to capture effects on fixed costs. A good compromise would be to include labour and fixed machinery costs into the analysis. However, to allow comparison with literature data, we limit our analysis to gross margins and their extension through the inclusion of pre-crop values or whole rotations.

Methods

We compiled yield and economic assessment data from the literature and conducted case studies in five geographic regions of the Legume Futures project. The literature included data from 29 experiments carried out in Europe that enabled the yield of cereals and rapeseed preceded by different pre-crops to be compared. Furthermore, the analysis included six studies comparing simple gross margins of legumes and non-legume crops and six studies comparing gross margins across similar rotations including and excluding legumes.

In the five case study regions, we conducted a structured expert survey in 2012/2013 to obtain crop production data on pre-crop and site-specific crop management and crop rotation rules using expert knowledge supplemented by statistical data. Emphasis was placed on pre-crop effects. The survey also specified several sub-sites for each region, such as different soil grades or lowland and highland, which determine yield levels and the range of suitable crops. The data were fed into a rotation generator to identify the full range of agronomically feasible rotations for each region and sub-site and to evaluate each rotation for economic and environmental performance.

Economic Evaluation from Crop to Rotation Level

To illustrate and address the economic value of legumes, we present, step by step, first the simple gross margin comparisons, then a review of the size and value of legume effects on subsequent crops, and lastly systematic economic evaluations for the case studies in a rotational context.

Crop-level profitability

Data from the Legume Futures survey revealed that legume gross margins ranged from $-\text{€}322/\text{ha}$ in Brandenburg (faba bean) to $+\text{€}574/\text{ha}$ in Sud-Muntenia (soybean) (Table 13.1). In Eastern Scotland, Västra Götaland and Sud-Muntenia, grain legumes had positive gross margins (i.e. they covered the direct costs of production). However, by comparing with data in Table 13.3, it is evident that they were competitive with wheat only in Sud-Muntenia. In contrast, gross margins were negative in Brandenburg and the Calabrian lowlands. Prices for grain legumes were comparable or slightly higher than those of cereals. In Germany for example, prices for grain legumes ranged between $\text{€}102/\text{t}$ for faba bean and $\text{€}182/\text{t}$ for pea, whereas prices for wheat were $\text{€}165/\text{t}$; in Calabria, legume prices of $\text{€}250\text{--}260/\text{t}$ compared with a wheat price of $\text{€}250/\text{t}$. These price differences do not compensate for the lower yields.

A compilation of six studies (Preissel *et al.*, 2015) shows a similar picture: low and unstable yields and comparably low prices resulted in a considerable gross margin deficit of grain legumes compared with alternative crops in 12 European

Table 13.1. Economic evaluation of legumes across the case study regions in selected site classes. (From survey data from the Legume Futures project.)

Country, region	Site class	Crop	Yield (t/ha)	Price (€/t)	Revenue (€/ha)	Variable costs (€/ha)	Gross margin (€/ha)
Germany – Brandenburg	Loam ^a	Faba bean	4.0	102	408	730	–322
	Loam ^a	Narrow-leaved lupin	2.5	150	375	679	–304
	Loam ^a	Pea	3.0	182	545	749	–204
Italy – Calabria	Lowland ^b	Faba bean	1.6	250	400	560	–160
	Lowland ^b	Pea	1.2	260	312	487	–175
UK – Eastern Scotland	Grade 3	Faba bean	5.0	197	986	701	285
	Grade 3	Pea	4.0	240	960	714	246
Sweden – Västra Götaland	Clay soil	Faba bean	3.1	168	521	397	124
	Clay soil	Pea	3.0	207	621	455	166
Romania – Sud-Muntenia	Chernozem	Pea	3.5	325	1138	828	310
	Chernozem	Soybean	2.5	440	1100	526	574

^aLocal site class 2.

^bRain-fed systems.

sites ranging from €70/ha to several hundred euros per hectare at eight sites; they were competitive with cereals at only four out of the 12 sites.

Pre-crop value of legumes

These crop-level gross margins do not take into account the pre-crop effects of the legumes. A meta-analysis of 29 experiments in Europe (Preissel *et al.*, 2015) showed that, where the yield of cereals following grain legumes was compared to that of cereals after cereals, a consistent yield difference of 0.5–1.6 t/ha was observed at both moderate and high fertilization levels. However, when cereals following grain legumes were compared to those following other broadleaved pre-crops, small yield increases of 0.1–0.4 t/ha were observed at moderate fertilization levels (up to 90 kg N/ha), but not at high fertilization levels (100–200 kg N/ha). Thus, the pre-crop effect of legumes on subsequent crop yield is similar to that of other broadleaved crops in intensive production systems. In Mediterranean water-limited sites, overall yield levels as well as legume effects are smaller (López-Bellido *et al.*, 2012). Mediterranean cereals often yielded 0.2–1.5 t/ha more after grain legumes than after cereals or sunflower. This yield increase in the subsequent cereal is worth between €20/ha and €300/ha compared with cereals in temperate sites (assuming a moderate wheat price of € 200/t). Prices play a crucial role in the overall evaluation.

Reduced costs in subsequent crops have a smaller effect on economic performance compared with increased revenue. In Europe, nitrogen fertilization of subsequent crops can be reduced by an average of 23–31 kg/ha without any yield losses (compiled in Reckling *et al.*, 2014a and in Preissel *et al.*, 2015). This would amount to cost savings of €18–24/ha at 2012 prices (for urea averaged over several countries; Eurostat, 2015a). Where nitrogen fertilizer use is restricted, nitrogen fertilization to subsequent crops can be reduced further by 62 kg/ha on average across estimates while maintaining adequate yields (i.e. the same yield as if the crop was grown following a cereal) (compiled in Preissel *et al.*, 2015). The ability of legumes to reduce weeds and diseases in subsequent crops has the potential to reduce costs by up to €50/ha (Luetke-Entrup *et al.*, 2003; von Richthofen *et al.*, 2006; Jensen *et al.*, 2010). Most break crops have the potential to improve soil structure, creating better establishment conditions for subsequent crops with less tillage and potentially saving about €20–60/ha in fuel costs (Luetke-Entrup *et al.*, 2003; Alpmann *et al.*, 2013a). The highest cost reductions can be achieved where legumes are grown in combination with reduced tillage, leading to potential cost reductions of €70–125/ha when reductions of fixed costs for machinery endowment and labour costs are included (Luetke-Entrup *et al.*, 2003). [Table 13.2](#) summarizes these different potential effects.

As [Table 13.2](#) shows, the impact of break crops is very variable depending on the situation and on the willingness and ability of farmers to diversify their cropping system. Whether these rotation-level effects fully compensate for the frequently lower gross margins of legumes depends on the environmental conditions, prices and crop management. Notably, legume rotational crop effects are similar to other break crops, so competition between legumes and these other break crops is a significant factor in determining farmers' cropping choices.

Table 13.2. Potential economic effects of grain legumes on subsequent winter wheat in temperate sites.^a

Effects on subsequent crops	Compared with cereal pre-crops		Compared with other break crops	
	Quantities per ha	Monetary value (€/ha)	Quantities per ha	Monetary value (€/ha)
Yield effects in subsequent cereals	+100 to +1500 kg	20–300	Up to +300 kg	< 60
Reduced N fertilization	By 23–31 kg N	18–24	By 23–31 kg N	18–24
Savings in weed and disease management	One to two treatments	< 50	No extra increase	–
Savings from better machinability		20–60		20–60
Savings from reduced tillage		70–125		70–125
Total range		130–560		38–209
Comparison: Legume futures Case studies		106–296		No effect

^aPrices are moderate assumptions based on 2012 data: wheat €200/t, N fertilizer €1.27/kg.

In the Legume Futures case studies, gross margins that take into account the pre-crop effect were calculated for all crops, confirming the pre-crop value based on literature estimates. Gross margins of winter wheat grown after grain legumes or rapeseed ranged from €322/ha to €689/ha (Table 13.3), and were €106–188/ha higher than after a cereal crop (€296/ha in Sud-Muntenia). Winter wheat grown after forage legumes generated additional gross margins of €116–301/ha.

Rotation-level profitability

A reliable estimate of legume profitability should compare the gross margins of full rotations. To represent the range of possibilities for sites, we generated a large number of feasible crop rotations using a crop rotation generator that takes rotational restrictions into account (see Reckling *et al.*, 2016a; Table 13.4). For a small number of sites we were unable to generate systems without legumes due to agronomic restrictions and a lack of crop combinations. For Romania, we excluded the most profitable rotations as these included common bean, a specialized food crop that only a few farmers could grow with specific marketing contracts.

Environmental and agronomic factors had a strong effect at all sites. Legume-supported rotations performed best compared with non-legume rotations in Romania, with an average advantage of €22/ha/year. They also had an advantage in the UK, with €6/ha/year and €10/ha/year on two soils suited to arable cropping. We found even greater advantages for a small number of Romanian

Table 13.3. Gross margins (GM) of winter wheat grown after cereals and legume pre-crops across the case study regions in selected site classes.

Country, region	Site class	Pre-crop type	Yield (t/ha) ^a	Price (€/t) ^b	Revenue (€/ha)	Variable		
						costs (€/ha)	GM (€/ha)	Additional GM (€/ha)
Germany – Brandenburg	Loam ^c	Cereal	5.7	165	942	779	162	0
	Loam ^c	Grain legume	6.8	165	1123	801	322	160
	Loam ^c	Forage legume	6.8	165	1123	801	322	160
Italy – Calabria	Lowland ^d	Cereal	3.2	250	800	626	175	0
	Lowland ^d	Grain legume	3.5	250	875	530	345	171
	Lowland ^d	Forage legume	3.6	250	900	530	370	196
UK – Eastern Scotland	Grade 3	Cereal	7.5	186	1395	986	409	0
	Grade 3	Grain legume	8.0	186	1488	973	515	106
	Grade 3	Forage legume	8.0	186	1488	963	525	116
Sweden – Västra Götaland	Clay soil	Cereal	6.1	188	1147	645	501	0
	Clay soil	Grain legume	7.1	188	1335	645	689	188
	Clay soil	Forage legume	7.7	188	1448	645	802	301
Romania – Sud-Muntenia	Chernozem	Cereal	3.6	232	835	688	147	0
	Chernozem	Grain legume	5.0	232	1160	717	443	296

^aYields are assessments by regional experts.

^bPrices of wheat are farm-level prices as given by the regional surveys.

^cLocal site class 2.

^dRain-fed systems.

rotations including common bean as a food crop and a small number of rotations under irrigation in Calabria (not shown). In Västra Götaland and Brandenburg, legume-supported rotations had €20–40/ha/year lower gross margins. In rain-fed sites in Italy, gross margins were up to €108/ha/year lower. Gross margins of arable systems were lowest in the German cases and highest in the UK cases for both legume-supported systems and systems without legumes. In Brandenburg, arable cropping systems on sandy soils had, on average, negative gross margins because of poor site productivity.

In forage systems, legume-supported rotations had an average advantage over rotations without legumes in all three regions where this comparison was possible (Table 13.4). Differences between regions were lower than in arable systems. The regional averages of the gross margins in forage legume rotation were €4–103/ha/year higher than those of the non-legume rotations.

Six other studies used rotation gross margin analysis to evaluate cropping systems (Table 13.5). Their results align with ours. Legumes were especially competitive in three Spanish case studies due to the low profitability of alternative crops, and in three French case studies. In Denmark and Switzerland, the studies identified no competitive grain legume rotations, as did our research for Sweden. For the UK, comparing the studies with our research (Table 13.4) yields a mixed result. In Germany, they identified competitive legume production in one organic and several conservation tillage systems, but only one competitive

Table 13.4. Generated rotations and the ranges of their gross margins across the case study regions and site classes.

Country, region	Sub-site	With/without legume	No. of rotations	Gross margin (€/ha/year)			Average difference
				Min	Max	Av. ^a	
Arable crop rotations							
Germany – Brandenburg	Loam ^b	– Legume	28	69	315	131	
		+ Legume	65	–3	214	76	–40
	Sand ^c	– Legume	18	–175	68	–3	
		+ Legume	35	–194	55	–24	–20
Italy – Calabria	Lowland ^d	– Legume	6	171	267	225	
		+ Legume	281	–15	233	116	–108
Sweden – Västra Götaland	Clay soil	– Legume	3,191	343	644	451	
		+ Legume	19,077	320	593	415	–36
UK – Eastern Scotland	Grade 1–2	– Legume	3,938	426	1,455	985	
		+ Legume	16,079	425	1,544	995	10
	Grade 3	– Legume	2,135	181	872	603	
		+ Legume	8,802	194	910	609	6
Romania – Sud-Muntenia	Chernozem	– Legume	20	272	432	369	
		+ Legume ^e	156	238	518	391	22
Forage-oriented rotations							
Germany – Brandenburg	Loam ^b	– Legume	374	59	429	185	
		+ Legume	792	92	462	217	22
	Sand ^c	– Legume	89	–35	262	80	
		+ Legume	343	–69	365	176	103
Italy – Calabria	Lowland ^d	– Legume	–	–	–	–	
		+ Legume	136	75	287	177	–
UK – Eastern Scotland	Grade 3	– Legume	23	638	922	737	
		+ Legume	20	660	874	746	9
	Grade 4	– Legume	8	372	502	423	
		+ Legume	10	389	572	465	42
Sweden – Västra Götaland	Clay soil	– Legume	136	430	590	481	
		+ Legume	132	311	614	485	4

^aAverage over all rotations with and without legumes, respectively, generated for a specific sub-site.

^bLocal site classes 1–2.

^cLocal site classes 3–5.

^dRain-fed systems.

^eExcluding common bean.

legume rotation in conventional production systems. These results partly align with observed production trends in these countries (FAOSTAT, 2014): grain legume production areas reduced slightly in Romania and Spain (17% reduction in 2000–2012), moderately in the UK, Italy, France and Germany (20–50% reduction) and substantially in Sweden and Denmark (50–80% reduction). The 40% increase in grain legume areas in Switzerland is not explained by these results, and the assessments do not adequately represent countries where production areas have increased since 2000 (mostly Eastern European countries).

Table 13.5. Competitiveness of legume-supported crop rotations with those not containing legumes according to modelled rotation gross margins. (From literature review by Preissel *et al.*, 2015.)

Region	Number of grain legume rotations compared			Reference
	Total	Competitive ^a	Not competitive ^b	
Germany: Bavaria (organic farming, food soy)	2	2	–	Weitbrecht and Pahl (2000) ^c
Denmark: Fyn	2	–	2	von Richthofen <i>et al.</i> (2006) ^d
France: Barrois, Picardie	2	2	–	von Richthofen <i>et al.</i> (2006) ^d
Germany: Saxony-Anhalt, Lower Bavaria	3	1	2	von Richthofen <i>et al.</i> (2006) ^d
Spain: Castilla y Leon, Navarra	3	3	–	von Richthofen <i>et al.</i> (2006) ^d
Switzerland: Vaud	1	–	1	von Richthofen <i>et al.</i> (2006) ^d
France: Burgundy, Moselle, Beauce	14	11	3	Hayer <i>et al.</i> (2012) ^d
France: Eure et Loir, Seine Maritime	2	2	–	LMC International (2009) ^e
Germany: Lower Saxony	2	–	2	LMC International (2009) ^e
Spain: Castilla-La Mancha	1	1	–	LMC International (2009) ^e
UK: East Anglia	2	–	2	LMC International (2009) ^e
Germany: Bavaria, Westphalia, Mecklenburg (plough and reduced tillage)	8	5	3	Luetke-Entrup <i>et al.</i> (2006) ^{c,d}
Spain: central (plough and reduced tillage)	3	3	–	Sánchez-Girón <i>et al.</i> (2004) ^{c,d}
Total	45	30	15	

^aAverage annual gross margin of grain legume rotation is higher or less than €10/ha lower than that of non-legume rotation.

^bAverage annual gross margin of grain legume rotation is more than €10/ha lower than that of non-legume rotation.

^cBased on experimental results.

^dOptimistic estimates of pre-crop effects: yield effect on first subsequent crop, N fertilizer saving, further cost savings due to reduced tillage.

^eConservative estimates of pre-crop effects: yield effect on first subsequent crop, some N fertilizer saving.

The comparison of the crop- and rotation-level profitability measures illustrates that crop-level comparisons neglect a sizeable share of the profitability of legumes and rarely find them competitive with other crops. The following section shows how crop choice can be fine-tuned for local conditions and the likely environmental impacts of competitive crop rotations with legumes.

Environmental Impact of Profitable Legume Rotations

Legume-supported cropping sequences are more economically viable than conventional gross margin analysis indicates. This leads to questions about the environmental impact of choosing economically competitive legume-supported cropping systems. Table 13.6 provides a comparison between the most economically viable rotations with and without legumes for their impact on nitrate leaching and nitrous oxide (N_2O) emissions (methods are described in Reckling *et al.*, 2014b).

The results show economic–environmental win–win situations for legumes in Eastern Scotland; while minor trade-offs compared with the most profitable non-legume cropping systems occur in Brandenburg and Sud-Muntenia. In Scotland, the legume rotation with faba bean substantially improves income and environmental impacts compared with the optimum without legumes. In Brandenburg, the legume rotation achieved only marginally lower income while substantially reducing emissions by 21% for nitrate and by 25% for nitrous oxide. In Sud-Muntenia, a legume rotation with soybean increases income and reduces nitrous oxide emissions, with a slight negative effect on leaching.

In contrast, in Västra Götaland and Calabria, even the most profitable legume rotations are economically poorer than rotations without legumes, while they lead to divergent environmental impacts. In Västra Götaland, the rotation with faba bean brings a sizeable loss of income compared with a rotation with linseed and no reduction in nitrate leaching, although nitrous oxide emissions are lower. In the Calabrian lowlands, the legume rotation would mean a sizeable income loss, while increasing leaching but substantially reducing nitrous oxide emissions.

When economic–environmental optimum rotations with legumes were compared with current farming (without legumes), these performed economically and environmentally better in Västra Götaland, Sud-Muntenia and Eastern Scotland (Reckling *et al.*, 2016b). Overall, the impact of the most profitable legume rotations on nitrate-N leaching was very site-specific and determined by the crop management, while nitrous oxide (N_2O) emissions were reduced by 12–35% in all selected legume-supported rotations compared with cropping systems without legumes. Our case studies showed highly positive environmental impacts for forage systems with legumes, but their economic assessment is highly complex and beyond the scope of this chapter. Reckling *et al.* (2016b) concluded from their analysis that legumes provide benefits to both the economic and the environmental performance of forage systems.

This assessment highlights that systematic cropping system design can be used to identify cropping systems with minor trade-offs or even win–win situations for improving the environmental performance of cropping. The assessment approach can also be used to identify and select those generated rotations that perform best in relation to specific indicators, such as rotations with the lowest emissions or highest N efficiencies, to provide a range of options for sustainable intensification of cropping systems in the case study regions.

Table 13.6. Comparison of most profitable legume and non-legume rotations, respectively, for arable production across the case study regions in selected sub-sites.

Country, region (sub-site)	Non-legume rotation	Gross margin (€/ha/year)	Legume rotation	Gross margin (€/ha/year)	Difference of legume to non-legume rotations ^a		
					Gross margin (€/ha/year)	Nitrate-N leaching (%)	Emission of N ₂ O (%)
Germany – Brandenburg (loam ^b)	Rapeseed, wheat, winter barley	128	Rapeseed, wheat, rye, rye, pea	111	–17	–21	–25
Italy – Calabria (lowland, rain-fed)	Rapeseed, wheat, rapeseed, wheat	267	Rapeseed, wheat, rapeseed, wheat, faba bean	233	–34	+16	–20
UK – Eastern Scotland (grade 3)	Rapeseed, winter barley, winter barley, winter barley, winter oat	509	Rapeseed, winter barley, winter oat, faba bean, winter barley	547	+38	–14	–8
Sweden – Västra Götaland (clay soil)	Rapeseed, wheat, linseed, wheat, spring barley	644	Rapeseed, wheat, faba bean, wheat, spring barley	593	–51	±0	–35
Romania – Sud-Muntenia (Chernozem)	Rapeseed, maize, wheat	432	Rapeseed, soybean, maize, wheat	518	+86	+7	–20

^aPositive values signify a higher impact of the legume-supported rotation.

^bLocal site class 2.

Potential for Increasing the Economic Value of Legume Grain

Although the competitiveness of legumes as crops is better than often estimated, the relatively low market value of the grain still discourages their production. There is an increasing potential for obtaining higher prices for legume grain by exploiting local feed markets. European-grown legume grain is under-valued in feed markets. A mix of locally grown legume grains and cereals is often cheaper than an equivalent mix of soybean and cereals. This gap has been explained by compounders' preference for the larger and more homogenous quantities offered by international traders (Sauermann, 2009; LLH, 2012; Alpmann *et al.*, 2013b). The purchase price for soybean meal almost doubled between 2006 and 2012 while the purchase prices for feed wheat increased at a lower rate (Fig. 13.1). Aramyan *et al.* (2009) predicted further increases in the prices of soy in markets that require genetically modified (GM)-free produce. Although changes in pea prices reflect changes in the price of soybean and wheat (LMC International, 2009), European pea and faba bean producer prices did not fully follow the price increases of soy-based feed ingredients. Consequently, the incentive for using pea or beans as locally grown feedstuff has increased. This is shown using a German feed calculator for pork feed ingredients (LLH, 2012). For given wheat and soybean purchase prices, this feed calculator computes the equivalent economic value of other products such as pea and faba bean on the basis of their most important contribution to pig feeds, namely the essential amino acid lysine and metabolizable energy.

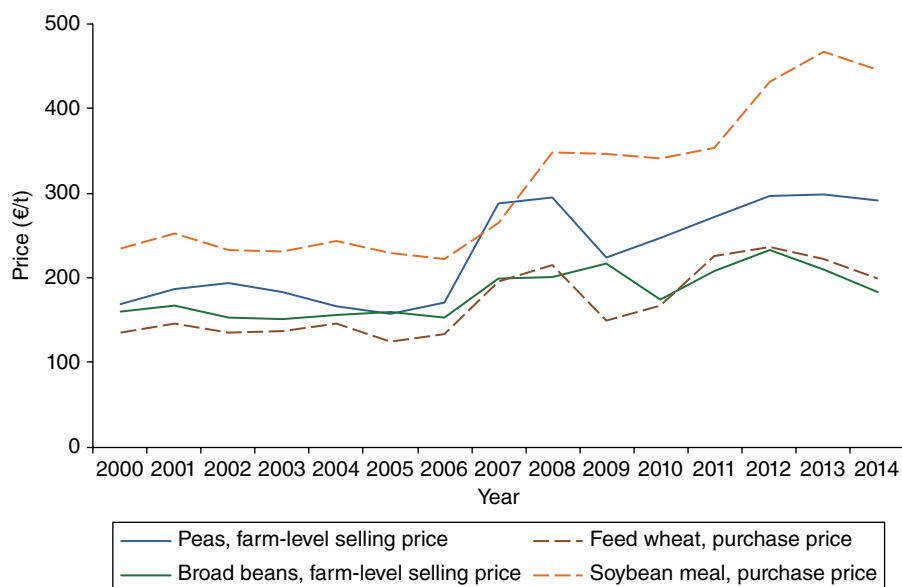


Fig. 13.1. Changes in the purchase prices of soy- and wheat-based feed and farm-level selling prices of major feed grain legumes in Europe. (From Eurostat, 2015a, b.)

Introducing the purchase prices for feed wheat and soybean meal into the calculator shows that, since around 2010, the equivalent economic value of pea and faba bean for pig production is considerably higher than the prices that the farmer would receive for selling those products (Fig. 13.2). In 2014, the difference between the value based on feed characteristics and the market price was more than €100/t (+55%) for pea and €28/t (+10%) for faba bean. In the German case study example, this surplus would raise pea gross margins to a positive value (see

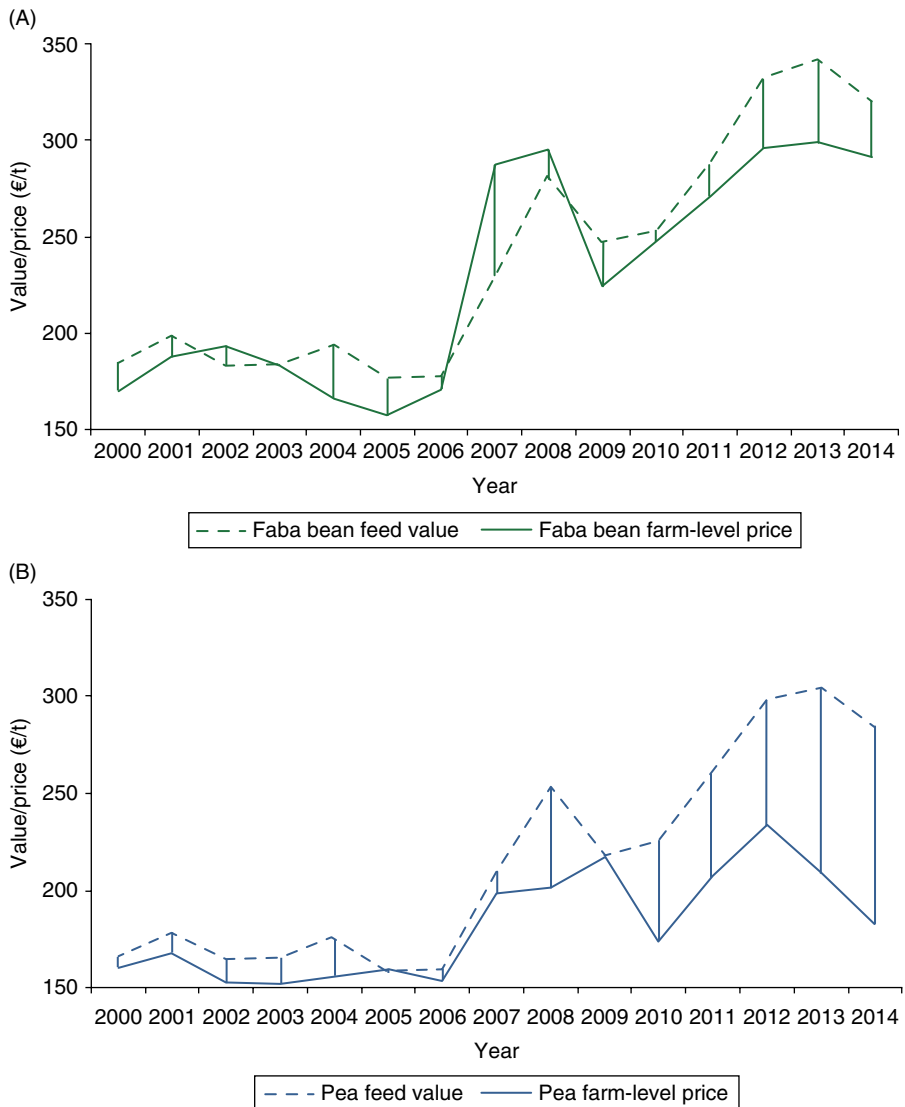


Fig. 13.2. Changes in farm-level (crop selling) prices and calculated feed value based on farm purchase prices for alternative feed ingredients (according to LLH, 2012) for faba bean (A) and pea (B), based on prices from Eurostat (2015a, b).

Table 13.1). Marketing legumes outside the feed sector holds further potential for improving their crop-level economic value. There are high-quality and high-price niches for legumes. Examples include the use of lupin in a number of new food products, such as PlantsProFood (Pro Lupin, 2014), or the non-food sector, including renewable resources for biorefineries (Papendiek *et al.*, 2012; Papendiek and Venus, 2014).

Conclusions

There is an economic under-valuation of legumes due to the lack of consideration of their wider effects in cropping systems. European-grown pea and faba bean are often under-valued in markets in relation to their feeding value. Thus, our calculations show that the economic value of legumes is substantially higher than commonly perceived. Legume-supported systems performed economically well where:

- the use of nitrogen fertilizers is restricted (e.g. organic farming, water protection areas);
- legume grain has a high value (e.g. soybean, grains for food uses, grain for local or on-farm feeding);
- other broadleaved crops are not particularly profitable (e.g. in parts of Spain); and
- grain legumes support effective reduced-tillage systems.

Through systematic cropping system design and economic evaluations at rotation level, we identified a number of cropping systems with the potential to improve both economic and environmental performance compared with standard rotations, which would not be identified using standard gross margin analysis.

Beyond these farm-economic (private) implications of legumes, we identified environmental (public) benefits of legumes that are not always recognized. A comprehensive assessment of entire supply chains could help to identify further levers for developing legume cropping and use. Increasing prices of nitrogen fertilizers and of soy imports will slightly improve the competitive situation of legumes, but this alone will not tip the balance to more diversified production systems throughout Europe. As the competitive advantage of cereals and oil crops is a result of technical and policy efforts in recent decades, we expect that similar efforts could raise the competitiveness of legumes to a similar level.

Acknowledgements

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References

- Alpmann, D., Braun, J. and Schäfer, B.C. (2013a) Analyse einer Befragung unter erfolgreichen Körnerleguminosenanbauern im konventionellen Landbau. Erste Ergebnisse aus dem Forschungsprojekt LeguAN. Paper presented at the DLG Wintertagung, Im Fokus: Heimische Körnerleguminosen vom Anbau bis zur Nutzung, Berlin, Germany, 16 January 2013. Available at: www4.fh-swf.de/de/home/forschung/forschungshighlights/leguan/leguan_3.php (accessed 25 April 2013).
- Alpmann, D., Braun, J. and Schäfer, B.C. (2013b) Fruchtfolgen zielgerichtet auflockern. *Land & Forst* 13, 26–28.
- Aramyan, L.H., van Wagenberg, C.P.A. and Backus, G.B.C. (2009) EU policy on GM soy: impact of tolerance threshold and asynchronous approval for GM soy on the EU feed industry. Report 2009-052. LEI Wageningen UR, The Hague, The Netherlands.
- Brisson, N., Gate, P., Gouache, D., Charmet, G., Oury, F.X. and Huard, F. (2010) Why are wheat yields stagnating in Europe? A comprehensive data analysis for France. *Field Crops Research* 119, 201–212.
- Bues, A., Preißel, S., Reckling, M., Zander, P., Kuhlmann, T., Topp, K., Watson, C., Lindström, K., Stoddard, F.L. and Murphy-Bokern, D. (2013) The environmental role of protein crops in the new Common Agricultural Policy. Report for study number PE 495.865 in series *Agriculture and Rural Development*. European Parliament, Brussels, Belgium.
- Cernay, C., Ben-Ari, T., Pelzer, E., Meynard, J.M. and Makowski, D. (2015) Estimating variability in grain legume yields across Europe and the Americas. *Scientific Reports* 5, 11171.
- De Visser, C.L.M., Schreuder, R. and Stoddard, F.L. (2014) The EU's dependency on soya bean import for the animal feed industry and potential for EU produced alternatives. *Oilseeds & fats Crops and Lipids* 21, D407.
- Eurostat (2015a) Purchase Prices of the Means of Agricultural Production (Absolute Prices) – Annual Price (From 2000 Onwards) [apri_ap_ina]. Available at: <http://ec.europa.eu/eurostat/data/database> (accessed 22 September 2015).
- Eurostat (2015b) Selling Prices of Crop Products (Absolute Prices) – Annual Price (From 2000 Onwards) [apri_ap_crpouta]. Available at: <http://ec.europa.eu/eurostat/data/database> (accessed 22 September 2015).
- FAOSTAT (2014) Production – Crops. Data from 1961 to 2012. Available at: <http://faostat.fao.org> (accessed 9 April 2014).
- Hayer, F., Bonnin, E., Carrouée, B., Gaillard, G., Nemecek, T., Schneider, A. and Vivier, C. (2012) Designing sustainable crop rotations using life cycle assessment of crop sequences. In: Corson, M.S. and Van Der Werf, H.M.G. (eds) *Proceedings of the 8th International Conference on Life Cycle Assessment in the Agri-Food Sector (LCA Food 2012)*, St Malo, France, 1–4 October 2012. INRA, St Malo, France, pp. 828–829.
- Jensen, E.S. and Hauggaard-Nielsen, H. (2003) How can increased use of biological N₂ fixation in agriculture benefit the environment? *Plant and Soil* 252, 177–186.
- Jensen, E.S., Peoples, M.B. and Hauggaard-Nielsen, H. (2010) Faba bean in cropping systems. *Field Crops Research* 115(3), 203–216.
- Jensen, E.S., Peoples, M.B., Boddey, R.M., Gresshoff, P.M., Hauggaard-Nielsen, H., Alves, B.J.R. and Morrison, M.J. (2011) Legumes for mitigation of climate change and the provision of feedstock for biofuels and biorefineries. A review. *Agronomy for Sustainable Development* 32, 329–364.
- Kirkegaard, J.A., Christen, O., Krupinsky, J. and Layzell, D. (2008) Break crop benefits in temperate wheat production. *Field Crops Research* 107(3), 185–195.
- Landesbetrieb Landwirtschaft Hessen (LLH) (2012) Berechnung der Preiswürdigkeit von Einzelfuttermitteln für Schweine nach der Austauschmethode Löhr. Excel-based

- calculation tool. Landesbetrieb Landwirtschaft Hessen. Available at: <http://www.ufop.de/agrar-info/aktuelle-meldungen/berechnung-preiswuerdigkeit-von-einzelfuttermitteln-nach-der-austauschmethode-loehr/> (accessed 22 September 2015).
- Leithold, G., Hülsbergen, K.J., Michel, D. and Schönmeier, H. (1997) Humusbilanzierung – Methoden und Anwendungen als Agrar-Umweltindikator. *Schriftenreihe der Sächsischen Landesanstalt für Landwirtschaft* 3, 19–28.
- LMC International (2009) Evaluation of Measures Applied Under the Common Agricultural Policy to the Protein Crop Sector. Main Report. LMC International, New York, Oxford, Kuala Lumpur. Available at: http://ec.europa.eu/agriculture/eval/reports/protein_crops/fulltext_en.pdf (accessed 4 March 2014).
- López-Bellido, L., Muñoz-Romero, V., Benítez-Vega, J., Fernández-García, P., Redondo, R. and López-Bellido, R.J. (2012) Wheat response to nitrogen splitting applied to vertisols in different tillage systems and cropping rotations under typical Mediterranean climatic conditions. *European Journal of Agronomy* 43, 24–32.
- Luetke-Entrup, N., Pahl, H. and Albrecht, R. (2003) *Fruchtfolgewert von Körnerleguminosen*. UFOP-Praxisinformation. Union zur Förderung von Oel- und Proteinpflanzen (UFOP), Berlin, Germany. Available at: www.ufop.de/files/3513/4080/9712/Koernerleguminosen.pdf (accessed 1 May 2014).
- Luetke-Entrup, N., Schneider, M., Stemann, G., Gröblichhoff, F.-F., Heißenhuber, A., Pahl, H., Hülsbergen, K.-J., Maidl, F.X., Herr, H., Sommer, C., Korte, K., Brunotte, J., Kreye, H., Lindwedel, V., Zieseniß, H., Gienapp, C., Schulz, R.R. and Propp, J. (2006) *Bewertung von neuen Systemen der Bodenbewirtschaftung in erweiterten Fruchtfolgen mit Körnerrraps und Körnerleguminosen*. Abschlussbericht über die Versuchsjahre 2001–2005. Fachhochschule Südwestfalen, Fachbereich Agrarwirtschaft Soest, Soest, Germany, 215 pp.
- Papendiek, F. and Venus, J. (2014) Cultivation and fractionation of leguminous biomass for lactic acid production. *Chemical and Biochemical Engineering Quarterly* 28(3), 375–382.
- Papendiek, F., Ende, H.-P., Steinhardt, U. and Wiggering, H. (2012) Biorefineries: relocating biomass refineries to the rural area. *Landscape Online* 27, 1–9.
- Peoples, M.B., Hauggaard-Nielsen, H. and Jensen, E.S. (2009a) The potential environmental benefits and risks derived from legumes in rotations. In: Emerich, D.W. and Krishnan, H.B. (eds) *Nitrogen Fixation in Crop Production*. Agronomy Monograph, no. 52. American Society of Agronomy, Crop Science Society of America, Soil Science Society of America, Madison, Wisconsin, pp. 349–385.
- Peoples, M.B., Brockwell, J., Herridge, D.F., Rochester, I.J., Alves, B.J.R., Urquiaga, S., Boddey, R.M., Dakora, F.D., Bhattarai, S., Maskey, S.L., Sampet, C., Rerkasem, B., Khan, D.F., Hauggaard-Nielsen, H. and Jensen, E.S. (2009b) The contributions of nitrogen-fixing crop legumes to the productivity of agricultural systems. *Symbiosis* 48(1–3), 1–17.
- Peri, M. and Baldi, L. (2013) The effect of biofuel policies on feedstock market: empirical evidence for rapeseed oil prices in the EU. *Resource and Energy Economics* 35(1), 18–37.
- Preissel, S., Reckling, M., Schläfke, N. and Zander, P. (2015) Magnitude and farm-economic value of grain legume pre-crop benefits in Europe: a review. *Field Crops Research* 175, 64–79.
- Pro Lupin (2014) PlantsProFood – Lupin Seeds for the Food Industry. Available at: http://www.plantsprofood.prolupin.de/tl_files/plants_pro_food/downloads/Broschur-PlantsProFood.pdf (accessed 12 November 2014).
- Reckling, M., Preissel, S., Zander, P., Topp, C.F.E., Watson, C.A., Murphy-Bokern, D. and Stoddard, F.L. (2014a) Effects of legume cropping on farming and food systems. Legume Futures Report 1.6. Available at: www.legumefutures.de/results/agricultureeffects.html (accessed 21 October 2016).
- Reckling, M., Hecker, J.-M., Schläfke, N., Bachinger, J., Zander, P., Bergkvist, G., Walker, R., Maire, J., Eory, V., Topp, C.F.A., Rees, R.A., Toncea, I., Pristeri, A. and Stoddard, F.L. (2014b) Agronomic analysis of cropping strategies for each agroclimatic region. Legume

- Futures Report 1.4. Available at: www.legumefutures.de/results/agronomicanalysis.html (accessed 21 October 2016).
- Reckling, M., Hecker, J.-M., Bergkvist, G., Watson, C., Zander, P., Stoddard, F.L., Eory, V., Topp, K., Maire, J. and Bachinger, J. (2016a) A cropping system assessment framework – evaluating effects of introducing legumes into crop rotations. *European Journal of Agronomy* 76, 186–197.
- Reckling, M., Bergkvist, G., Watson, C.A., Stoddard, F.L., Zander, P., Walker, R., Pristeri, A., Toncea, I. and Bachinger, J. (2016b) Trade-offs between economic and environmental impacts of introducing legumes into cropping systems. *Frontiers in Plant Science* 7, 669.
- Robles, R. (2011) The economics of oil-seed crops for energy use: a case study in an agricultural European region. *Problems of the World Agriculture/Problemy Rolnictwa Światowego* 11(3), 115–125.
- Robson, M.C., Fowler, S.M., Lampkin, N.H., Leifert, C., Leitch, M., Robinson, D., Watson, C.A. and Litterick, A.M. (2002) The agronomic and economic potential of break crops for ley/arable rotations in temperate organic agriculture. *Advances in Agronomy* 77, 369–427.
- Sánchez-Girón, V., Serrano, A., Hernanz, J.L. and Navarrete, L. (2004) Economic assessment of three long-term tillage systems for rainfed cereal and legume production in semiarid central Spain. *Soil and Tillage Research* 78, 35–44.
- Sauermann, W. (2009) Körnerleguminosen konservieren oder silieren. Mit Ackerbohnen, Futtererbsen und Süßlupinen Futterkosten senken. *Landwirtschaftliches Wochenblatt Schleswig-Holstein* 27, 23–24.
- von Richthofen, J.-S., Pahl, H., Bouttet, D., Casta, P., Cartrysse, C., Charles, R. and Lafarga, A. (2006) What do European farmers think about grain legumes? *Grain Legumes* (45), 14–15.
- Weitbrecht, B. and Pahl, H. (2000) Lohnt sich der Anbau von Körnerleguminosen? *Ökologie & Landbau* 116, 39–41.
- Zander, P., Amjath-Babu, T.S., Preissel, S., Reckling, M., Bues, A., Schläfke, N., Kuhlman, T., Bachinger, J., Uthes, S., Stoddard, F.L., Murphy-Bokern, D. and Watson, C. (2016) Grain legume decline and potential recovery in European agriculture: a review. *Agronomy for Sustainable Development* 36, 1–20.

14 Optimizing Legume Cropping: the Policy Questions

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Abstract

The cultivation of legumes is low in Europe. Public policy incentives and/or regulations have a role to play in changing this. This chapter examines six such policies. The CAPRI (Common Agricultural Policy Regional Impact) model, a partial equilibrium model for the agricultural sector, is used to simulate the effects of these policies and compare them to what would happen if no policy action were taken. Five of these policy scenarios are aimed at grain legumes (pulses and soybean), and one at forage legumes (in particular, clover). Three of the policies could be incorporated into the Common Agricultural Policy, whereas the other three are more general in nature: related to consumption, international trade and climate-change mitigation. It is the latter two that are likely to have the most significant effect on the cultivation of grain legumes.

Introduction

Preceding chapters in this book describe cropping and forage systems containing legumes which, if realized, would contribute to the sustainable development of European agriculture. The overall costs and benefits of these systems for farm businesses and society have been clarified – weighing the effects on environmental sustainability and social well-being. This chapter addresses the question of how policy can help to promote these systems. It is based on research conducted in the Legume Futures project (Helming *et al.*, 2014).

There are two reasons why policy intervention is needed. First, many farmers lack reliable information on the most suitable legume crops and how to integrate them into their farming systems. This is a consequence of the decline in on-farm technical knowledge about legumes as well as the lack of progress through research.

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Second, even though legumes can be a profitable option for farmers, in many situations other crops provide more net revenue. Hence, legumes are used less in farming systems than is desirable from a societal point of view. In the economist's parlance, there are positive economic externalities in growing legumes. This calls for policies to increase the area under legumes.

What, then, can these policies be? It has been famously said that there are three kinds of policy instruments: carrots, sticks and sermons (Bemelmans-Videc *et al.*, 2003). Carrots are incentives (positive or negative) that make the desired decisions more attractive or undesired options less attractive. They narrow the gap between private and social costs and benefits using either subsidies or penalties; we may also say that they are a way to internalize economic externalities. Sticks are regulations that force private decisions more in line with the desired state. Sermons are what Anderson (1977) calls structured options: programmes that individuals can use as they see fit. In our case, a sermon can consist of information provided to land users on how to incorporate legumes into farm practices. Another possibility in the 'sermon' category is the labelling of the products of particular farming systems, such as is currently done for organic production. Many farmers will also respond to the opportunity to produce in a more sustainable way, as long as the cost is not excessive in relation to their (private) benefits.

Farming in Europe is heavily affected by European Union (EU) policies, and the Common Agricultural Policy (CAP) offers plenty of opportunities for influencing farmers' behaviour. This chapter focuses on options that may be envisaged as part of the CAP, although possible policies to be formulated at national or regional level will also be considered. Growing legumes can be influenced also by policies outside the realm of agriculture itself. We first discuss how the CAP has influenced legume growing in Europe until now. From there we consider the formulation of possible policies within and outside the CAP framework which may help to promote the legume-inclusive systems described in this book. These policies have been simulated with the help of the Common Agricultural Policy Regional Impact (CAPRI) model, a partial equilibrium model for the agricultural sector in a European context.

Legumes and the CAP

The area under grain legumes in Europe declined from 5.8 million ha in 1961 to 1.9 million ha in 2011 (Eurostat, 2015). This is not solely due to the CAP, it is also part of a wider process of change: increased consumption of animal products to the detriment of vegetable sources of protein facilitated by the large-scale importation of soy to feed the expanding European livestock herd. However, measures under the CAP have contributed to the decline. Market support for arable crops focused on cereals in the early years of the CAP, leading to an expansion in wheat and barley at the expense of pulses.

Policy makers saw the decline in legumes as problematic: the role of legumes in enhancing soil fertility was well known. Also in the interest of food security (a principal objective of the CAP), there was a case for maintaining protein-rich legume crops. In order to rectify this imbalance, market support for 'protein crops' (pea, faba bean and sweet lupins) was introduced in 1978. This stopped the decline

in the countries that were then members of the Common Market (Fig. 14.1). In the late 1980s there was even an increase due to the need for protein-rich animal feed. The 1992 ‘MacSharry’ reform of the CAP, designed mainly to curb excess production, restricted support to cereals and thereby probably helped the relative position of legumes. At the same time, however, the Blair House Agreement put a ceiling on the support for European oilseeds (which includes the legume soy-bean): a maximum was set on the land area that could receive support, as well as on the amount of oilseed by-products that could be harvested from set-aside land (where non-food crops including legumes could be grown). It is not certain that this agreement actually enforced a decline in legumes, but it did not help their growth potential.

The protein crop premium was finally abolished in 2006, although there was some limited support for these crops under Pillar 1 (production support) until 2012. This support was given only in some countries at their discretion and it was coupled to the cropped area, not to production. The decoupling process was completed in 2012 and this limited area support was discontinued. However, in some countries (e.g. Hungary, Poland, some regions in Spain and Italy) legumes still continued to be subsidized under Pillar 2 (rural development) because of their environmental benefits. This support was also area-based.

A new phase of the CAP began in 2014. Pillar 1 now consists primarily of direct payments on a per-hectare basis, decoupled from production. However, 30% of these payments are conditional on so-called greening measures by the farmer: (i) crop diversification (for larger arable farms); (ii) maintenance of permanent grassland; and (iii) maintaining so-called ecological focus areas (EFAs) on 5% of farmland, later to be expanded to 7%. Both the crop diversification requirement

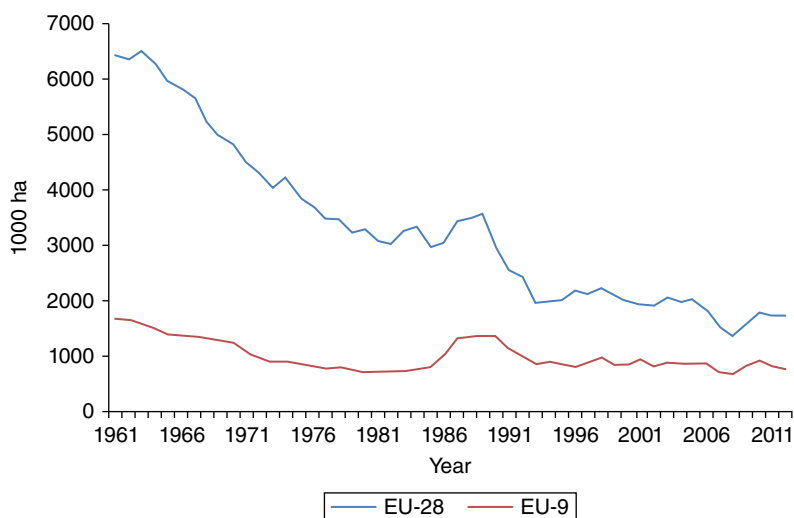


Fig. 14.1. Area under grain legumes in the European Union (EU) (from FAOSTAT, 2015). EU-9: the six founding members of the European Communities plus the three countries that joined in 1973 (the UK, Ireland and Denmark); EU-28: the 28 members of the EU since 2013.

and the EFA may favour legumes. Exactly how EFAs are defined is left to member states, but permitted practices include natural or semi-natural vegetation such as buffer strips next to watercourses or hedgerows, or cultivation with annual rotation without the use of agrochemicals (European Commission, 2013). Growing legumes could fit in this policy, as has happened in, for example, the UK, but this remains controversial in the environmental policy community (Dicks, 2014; Ehlers *et al.*, 2014).

In addition to these greening requirements, member states may also still include support for legume cultivation under the agri-environment schemes in Pillar 2, as in the past. These schemes are co-financed by the member states themselves.

Forage legumes may be grown as monocultures or included in a grass sward. No measures have been undertaken under the CAP to promote the growing of forage legumes specifically. Data on the use of forage legumes are patchy, but the general trend of intensification in farming has led to grassland management that favours those species which provide the most productive fodder in terms of energy and respond positively to applied nitrogen. This notably means an increase in grasses at the expense of broadleaved plants which include legumes (Boatman *et al.*, 2007).

Policy Scenarios

Judging from the considerable environmental benefits of growing legumes combined with the current negative trend in producing them in Europe, there appears to be a good case for policy intervention. The challenge is to find policies that could bring about the required result without negative side effects. This is where economic modelling can help. Policies can be cast in the form of possible scenarios, each of which is simulated by the model so as to explore its impact on the environment as well as on the economy. The outcomes of these scenarios are compared not with the present situation but with a counterfactual indicating what would happen in the absence of said policy. As part of the Legume Futures project, we modelled different scenarios relating to policies that might be used in future to increase the production of legumes. The impact of these policies is compared with a reference scenario describing the situation in 2020 if no new measures are taken to increase the growing of legumes. The policies are as follows.

- 1. Hectare premia for grain legumes.** Premia existed in the CAP in the recent past. Unlike the policy before the 2003 reform, it would be linked to area rather than production.
- 2. Legumes included in EFA.** Under this policy, legume production would fulfil the EFA obligation under the current CAP. As mentioned above, this would be controversial as the EFA is meant for semi-natural vegetation. However, legumes have ecological benefits and the policy could include restrictions on the use of agrochemicals so as to maximize these benefits.
- 3. Compulsory forage legumes.** A compulsory percentage of clover in grass swards is modelled, but other legumes could be used. The simulated regulation is a requirement to have a proportion of clover of 25% in all grassland.

4. Meat tax. This scenario includes a tax on meat consumption, coupled with a subsidy on vegetable protein (which legumes produce in large quantities). Such a policy would not only address the need to grow more legumes, but also more generally the environmental burden of the rapid increase in livestock production.

5. Carbon taxes in agriculture. Under current policy, farmers are not included in the emission trading scheme, although fertilizer manufacturers are. Under the scenario examined here, all farmers would be taxed for the amount of greenhouse gas (GHG) emissions (not only carbon dioxide (CO₂), but also methane (CH₄) and nitrous oxide (N₂O)). Conversely, the reduction of emissions through carbon storage would be rewarded.

6. Genetically modified (GM) soy imports. Finally, the potential future effects of an existing policy are examined – effects that are not considered in the reference scenario. European livestock production has become heavily dependent on imported soybean as a source of protein. Most of this soybean is GM and subject to a lengthy process of approval. This presents a problem for the future: as more and more GM cultivars are developed, the approval process will lag increasingly behind the commodity markets. Moreover, since there is a zero-tolerance policy in force for the presence of non-approved cultivars in soy shipments, it will become increasingly risky for traders to ship soy to the EU, as the entire shipment may be rejected without compensation if trace quantities of non-approved GM cultivars are found in the load. This can cause disruptions in the soy trade (Nowicki *et al.*, 2010). Under the scenario, the worst case is assumed, where a large proportion of imported soybean cultivars have not been approved and zero tolerance for traces of such cultivars is maintained. The resulting shortage of imported soy would promote the production of soybean and other grain legumes in the EU.

The first two of these policies are standard components of the CAP. The third one could theoretically be included in the CAP as well. The meat and carbon taxes are not CAP policies, but could be undertaken as general policies to promote a healthier lifestyle (the meat tax) or to mitigate climate change (the carbon tax). The last scenario is a consequence of an existing policy that could lead to stimulating legume production in Europe. Because of the risk of severe disruption of livestock production, it is unlikely that the current policy on importing GM soybean for feed will continue in its present form: the project (Nowicki *et al.*, 2010) in which it was modelled was conducted to apprise the European Commission of the risks involved.

Simulating the Policies: the CAPRI Model

These policies were simulated with the CAPRI model. It is a partial equilibrium model for the agricultural sector and, as the name indicates, it can specify the impact of CAP measures on farmers' behaviour for each region (according to the Nomenclature of Units for Territorial Statistics (NUTS) 2 territorial classification) in EU member states, as well as in some other European countries (Britz *et al.*, 2007).

The model consists of a supply module and a market module (Woltjer *et al.*, 2011). The supply module represents up to ten farm types in each NUTS2 region. The data come from Eurostat's Economic Accounts for Agriculture with 2009 as the base year. The farm models have fixed input-output coefficients for each production activity with respect to land and intermediate inputs, in many cases with a low- and high-yield variant. Fertilizer and feed requirements are taken into account. A land supply module allows for land leaving and entering the agricultural sector and transformation between arable and pasture land, both in response to relative price changes.

The market module is a comparative static global multi-commodity model. It covers 47 primary and secondary agricultural products, and models trade between 60 countries grouped in 28 trade blocks. Among these agricultural products are two legume categories, pulses and soybeans. Apart from marketable agricultural outputs, it contains a specific sub-component that models the feed market. The behavioural equations for supply, feed, processing and human consumption have flexible functional forms. Calibration algorithms make the coefficients in these functions consistent with micro-economic theory.

Labour and capital costs are captured by a non-linear cost function. These cost functions are calibrated so as to mimic the base data and to capture information about supply elasticities. The models allow for much of the detail in CAP regulations. Prices are exogenous in the supply module and provided by the market module. Grass, silage and manure are non-tradable and receive accounting prices based on opportunity costs.

CAPRI uses templates that are filled with different parameter sets for different regions and products. This reduces maintenance cost and makes results comparable across products, activities and regions. The modular set-up allows independent use of the different components.

The CAPRI output includes economic variables such as land areas for different crops, crop and animal production, agricultural prices, farm incomes and budgetary costs, and also environmental variables such as GHG emissions, nitrate and phosphate surpluses, and energy use.

Since CAPRI is a partial equilibrium model, it cannot forecast what happens in other sectors of the economy, outside agriculture. This is another reason why the policy scenarios are structured in such a way that they are neutral in terms of government budget and in taxes and subsidies for farmers. Were this not the case, we would have to take the effect of our policies on other sectors into account, and a general equilibrium model would be needed, which cannot provide the kind of detailed output on agriculture that CAPRI can.

Like most economic models, CAPRI is designed to simulate effects in the short and medium term, so we have modelled 2020 as the target year. This is a limitation, as a significant part of the impact of growing legumes is a long-term process, but we cannot know what trade and prices will do in the longer run.

Another limitation that has some effect on our outcomes is that CAPRI can only simulate the expansion or contraction of existing crops in any particular region, not the introduction of a crop in a region where it was not grown before. The model contains parameters for all crops that are grown in a region, and not for those that might be grown. Finally, it may be noted that Croatia is not included in the simulation, as it was not an EU member state in the base year.

Results

It must be remembered that we cannot pronounce on the probability of any of the scenarios coming to pass. The reference scenario is merely a continuation of recent trends. The GM scenario describes what might happen under certain new circumstances if current policies are not modified. The new circumstances are highly likely, but current policy will probably be modified in response to those circumstances. It is very important also to remember that the scenario changes are in relation to the reference scenario.

Reference scenario

In the reference scenario (i.e. with a continuation of current trends) there will be a further decline in the cultivation of legumes. The area under pulses will decrease by 327,000 ha or 24% over the period 2009–2020. However, cultivation of soybean will increase, by 213,000 ha or 70%, meaning an overall net loss of 114,000 ha for grain legumes or 7% of the grain legume area in 2009. Figures per country are shown in [Table 14.1](#). Large increases in production under the reference scenario are predicted due to an expansion of soybean cultivation in countries where the climate is suitable and where the crop is presently grown only on a small scale.

Hectare premium for grain legumes

The rationale behind this policy would be that legumes are often less profitable than other crops, but that they provide environmental benefits. Since these accrue to society at large rather than to the farmer who delivers them, the farmer would tend to produce fewer legume crops than would be in the interest of society. We have defined the premium in such a way that up to 2% of the CAP budget for direct farm payments (Pillar 1) in any one NUTS2 region is allocated to legumes. In order to avoid excessive premia per hectare in regions with very small areas under legumes, the premium cannot be higher than the average direct farm payment per hectare at national level. As the area under legumes increases with the premium, the payment per hectare is reduced so as to avoid overshooting the budget. The resulting annual payments in the scenario range from €70/ha (Latvia) to €425/ha (Greece).

This leads to an increase of the area under grain legumes of 12% in 2020 compared with the reference scenario. This is not very large, but at least it means that there will be a slight increase, as opposed to the decrease projected in the reference scenario. As can be seen in [Fig. 14.2](#), the effect differs between regions, with some regions even experiencing a decrease in the area under legumes. This is probably due to price changes: as more legume products come onto the market, the price will be reduced and this will make cultivation unattractive to some farmers. This is the case in Romania and Bulgaria, where direct farm payments

Table 14.1. Area under grain legumes in 2009 and in 2020 under the reference scenario.

Country	2009		2020 (reference scenario)		Percentage change in area (%)
	Thousand ha	As a percentage of arable (%)	Thousand ha	As a percentage of arable (%)	
Austria	47	3.3	84	5.5	80
Belgium	2	0.2	1	0.1	-68
Bulgaria	8	0.8	45	1.3	474
Cyprus	2	0.9	1	0.8	-19
Czech Rep.	36	0.7	69	2.3	92
Denmark	7	0.3	2	0.1	-75
Estonia	5	0.2	5	0.8	-7
Finland	7	0.3	7	0.3	3
France	263	1.3	221	1.1	-16
Germany	83	0.7	81	0.6	-2
Greece	21	0.6	19	0.6	-8
Hungary	52	4.3	87	1.8	68
Ireland	4	0.4	3	0.3	-11
Italy	210	2.1	92	0.9	-56
Latvia	3	1.6	2	0.2	-39
Lithuania	47	0.3	43	2.1	-10
Malta	< 1	0.2	< 1	0.2	-33
Netherlands	3	0.3	0.5	0.0	-84
Poland	129	8.8	79	0.6	-39
Portugal	15	0.7	4	0.2	-74
Romania	104	14.2	148	1.5	43
Slovakia	20	1.4	24	1.6	18
Slovenia	1	0.6	6	2.7	582
Spain	315	1.8	309	1.8	-2
Sweden	26	1.0	15	0.6	-41
UK	242	4.0	191	3.1	-21
EU-27	1652	1.3	1538	1.2	-7

are lower to begin with, so the premium may not be sufficient to offset the lower price for the produce.

Apart from the increase in area under legumes, the policy will have other effects on land use. First, it becomes more attractive to grow crops rather than to maintain pasture, so some grassland will be converted to arable land: about 42,000 ha compared with the reference scenario. Second, because direct farm payments decline generally where legumes are not grown, some land will be taken out of production. This will occur on 27,000 ha, or 0.015% of the total utilized agricultural area (UAA), mostly in Scotland and north-western Spain.

Economic effects of the legume premium include the following.

- Lower imports of soy and pulses.
- Redistribution of direct farm payments in favour of farmers who grow legumes at the expense of those who do not (including livestock farmers); the total amount per country does not change.

- Although total CAP payments do not change on balance, there is an increase in overall farm income by 0.08% due to slightly higher prices for all crops other than legumes.
- There is on balance a slight advantage to consumers (€36 million/year) due to price effects – although most crops become more expensive, animal products become cheaper.
- On the other hand, there is a cost to taxpayers (€50 million/year), and since consumers are also taxpayers there is no net gain.
- The net effect on the economy is a positive €139 million, or 0.01% of gross domestic product (GDP).

Legumes included in EFAs

If growing legumes fulfils the EFA requirement under the new CAP, the farmer would choose between growing legumes and various types of fallow: (i) simply not using the land; (ii) buffer strips; (iii) hedges; or (iv) some other form of semi-natural vegetation. His or her choice will depend on the costs and revenues of options in different regions. Overall, we forecast an increase in uncultivated land

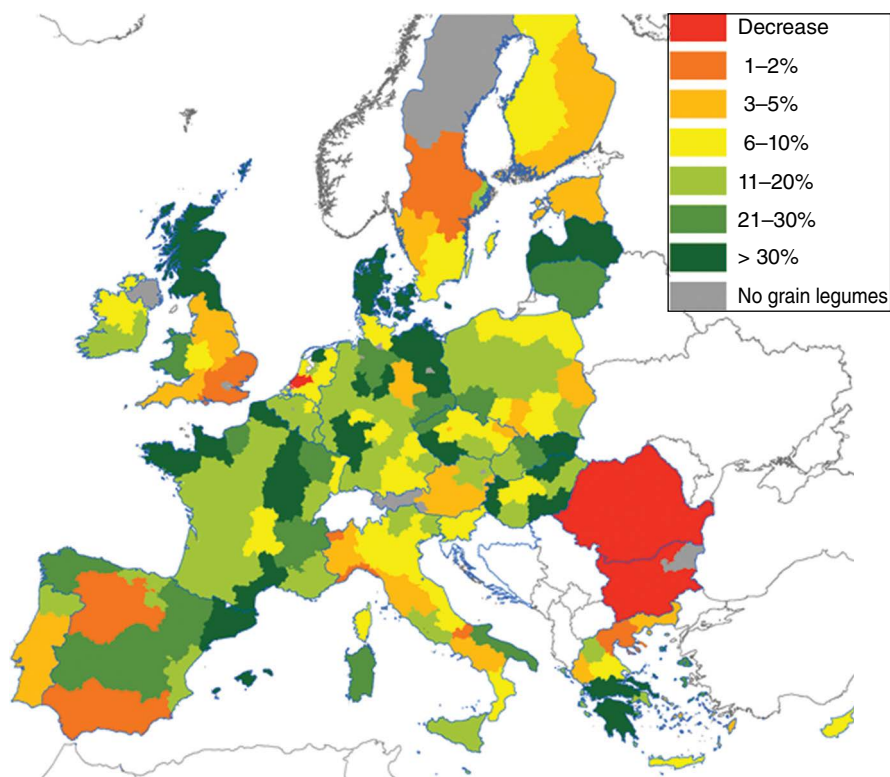


Fig. 14.2. Change in cultivation of grain legumes under hectare premium scenario.

of almost 3 million ha while legumes increase by no more than 50,000 ha relative to the reference scenario. Once again, the effect differs strongly by region, with many regions showing an even stronger decrease compared with the reference scenario, with significant increases elsewhere. Moreover, the geographical pattern of increase and decrease of legumes differs from that under the hectare premium scenario.

These results seem counter-intuitive: the policy implicitly subsidizes legumes, so how can this lead to a decline in some regions (although not a decline in the EU as a whole)? To understand this, we must consider that the costs and revenues of growing legumes in comparison with leaving the land fallow are different in each region. Moreover, the overall increase in legume cultivation (albeit slight) causes a decrease in price. In regions where the profitability of legumes is marginal, this price change may tip the balance and cause a decrease in their cultivation. In such regions, the area under legumes will be small, meaning that a decrease of a few hundred hectares may constitute a decrease of over 10%. The hectare premium, on the other hand, may be sufficient to persuade these farmers to increase the area under legumes. It is precisely such counter-intuitive results that make a model such as CAPRI a useful tool for predicting the impact of agricultural policies.

The environmental and welfare effects of the policy will be similar to those of the hectare premium scenario, but even smaller – in line with the limited effect on land use.

Compulsory forage legumes

It is estimated that grassland in the EU contains only 5% clover on average, but the percentage varies widely per country. An increased share of clover will reduce the dry matter yield of the grassland where it is already heavily fertilized, but it is more difficult to say what happens to nutritional value (energy and protein). The data coverage on this point is limited, and the outcome varies per country for those countries where data are available. Hence, only the impact on dry-matter yields could be modelled in CAPRI.

From the point of view of a farmer who uses synthetic nitrogen fertilizer, increasing the proportion of clover means that additional feed needs to be purchased in order to have the same total quantity of stockfeed (in terms of dry matter) for the same number of animals. The farmer saves money on the fertilizer he or she does not need to use, but this saving is less than the extra feed cost. The net increase in cost is on average 2.5%. The resulting lower profitability of livestock will lead to a slight decrease in the livestock herd. As with other policies, the effect will not be the same throughout Europe, and under some conditions a grass–clover mix can be more profitable than pure grass, such as when the ratio of fertilizer price to milk price reaches a tipping point (Humphreys *et al.*, 2012; see Chapter 9, this volume).

Compared with the alternative of fertilized pure-grass swards, grass–clover mixtures produce lower emissions of N₂O and ammonia (NH₃), as well as leading to a decrease in CO₂ emissions from the manufacture of nitrogen fertilizer (see [Table 14.2](#)). Methane emissions also decrease, due to the reduction in livestock herd.

Table 14.2. Environmental impact of the forage legumes scenario.

Type of impact	Difference with reference scenario (%)
Ammonia emissions	-0.7
Methane emissions	-1.4
Global warming potential	-2.1
N input with mineral fertilizers	-15.0
N input with manure (excretion)	-1.2
N input with crop residues	-3.3
Biological nitrogen fixation	130.8
Atmospheric N deposition	0.0
N export with crop products	-2.5
N surplus total	-4.6

Meat tax

The meat tax policy is implemented in such a way that 2.5% of meat consumption is substituted by vegetable proteins, in particular, pulses. This is done by first taxing the margin between producer price and consumer price of meat products, such that consumption will decrease by the target 2.5%. Next, a subsidy is applied to the same margin in pulses, until their consumption rises by an amount equivalent to 2% of meat consumption (pulses contain more protein than meat, so the protein content of food remains the same). These changes are iterated until the increase in protein consumption from pulses is equal to the decrease in meat protein for the EU as a whole. The result is achieved by taxing meat production by an average 7% of the margin between producer and consumer price, and by subsidizing the same margin in the pulse price by, on average, 50%.

Since this is not a specifically agricultural policy but a general one (it could be implemented either at European or at national level, although only the European option is considered here), its effect on land use is indirect. The direct effect is on prices: consumer prices for pulses go down while the price paid to producers goes up, and the reverse happens for meat products (Table 14.3). CAPRI projects a decrease of meat consumption by 1.1 million t or 2.5%, whereas human consumption of pulses goes up by 865,000 t or 72%. However, not all of this change in consumption means a parallel change in production: net exports of meat increase and so do net imports of pulses; moreover, less pulse produce is used for animal feed. On balance, production of meat decreases by 1.5% and domestic production of pulses increases by 2.9%.

The area under pulses increases proportionally to the increase in production, but the production of soybeans does not increase, because the decrease in meat consumption reduces demand for soy. Hence, the increase in area under legumes as a whole for the EU-27 is only 25,000 ha. This represents a 1.7% increase as a percentage of the arable area – lower even than the previous policy scenario. The spatial pattern is similar to that of the EFA scenario: decreases mostly in the Netherlands, Ireland, Sweden, Finland, southern Greece and the Italian islands; increases in Denmark, Brittany and the Baltic states.

Table 14.3. Price effects of the meat tax scenario.

Product	Change under meat tax scenario					
	Reference scenario (2020)		Absolute difference with reference		Percentage difference with reference	
	Producer price (€/t)	Consumer price (€/t)	Producer price (€/t)	Consumer price (€/t)	Producer price (%)	Consumer price (%)
Pulses	278	2518	14	-855	4.9	-34.0
Beef	3408	6798	-84	159	-2.5	2.3
Pork meat	1592	4436	-55	157	-3.4	3.5
Sheep and goat meat	5388	5747	-51	138	-0.9	2.4
Poultry meat	1578	4668	-16	94	-1.0	2.0

Total GHG emissions from agriculture decline by 0.4%, not so much due to the increase in legumes but more to a decline in livestock production, which in turn means less land needed for feed. Ammonia emissions are reduced by 0.6% for the same reason.

Farmers' income declines under this scenario, particularly in areas with few legumes but much livestock, which is the case over much of north-west Europe. This might lead to further farm consolidation, although that phenomenon is not modelled in CAPRI. The increase in farming scale is primarily driven by technology, but smaller farmers are forced out more quickly where margins are squeezed.

Carbon tax for agriculture

The carbon tax scenario is not modelled as an overall tax on GHG emissions, but only on emissions from the agricultural sector. CAPRI is not suited to simulating the effect of taxes on all sectors. In the particular version of the scenario discussed in this chapter, a price for emission rights of €72/t of CO₂ equivalent is used. This price is based on the Stern Review of 2006, corrected for inflation, and is the price that would be necessary to keep climate change at an acceptable level. It is much higher than recent prices on the emissions market. The policy means that farmers are taxed for all GHG emissions (including nitrous oxide from nitrogen fertilizer use), and conversely rewarded for diminishing these emissions (including the storage of carbon in the soil).

Under these conditions, the cultivation of legumes would increase by 62%, to 3.5 million ha in 2020. This increase would take place in almost all parts of Europe (Fig. 14.3). In many regions, notably in parts of Spain, France, Romania, Germany and Scotland, the area under grain legumes would more than double.

There are numerous other effects. Most importantly, livestock farming would become less profitable, and beef cattle in particular would decrease. The total utilized agricultural area would decrease by 1.6%, mostly because of a decrease in intensive grassland. The area under fallow would increase significantly, as this

would avoid GHG emissions. The same explains a shift from intensive to extensive grassland (which would be richer in clover): the latter attracts less carbon tax, and the lower land price (another result of this policy) would make extensive land use more interesting to the farmer.

The increases in area under legumes and fallow land, along with the shift from intensive to extensive grassland, all produce positive and fairly significant environmental effects (Table 14.4). The actual impact is even larger, as not all

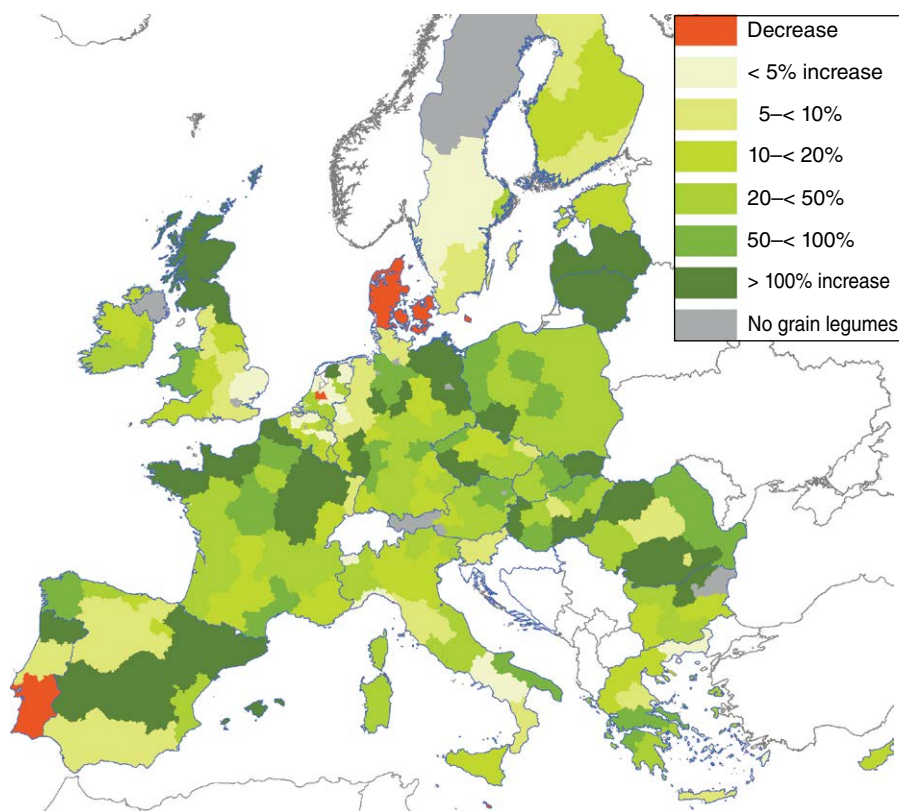


Fig. 14.3. Change in cultivation of legumes under carbon tax for agriculture scenario.

Table 14.4. Environmental impact of carbon tax scenario.

Type of impact	Reference (1000 t)	Carbon tax (% change)
N input from mineral fertilizer	10,690	-4.4
N input from manure	9,086	-3.6
Nitrous oxide emissions	743	-3.4
Methane emissions	7,899	-3.6
Total GHG emissions from agriculture (CO _{2e})	396,156	-3.6
Ammonia emissions	2,412	-3.3

CO_{2e}, Carbon dioxide equivalent; GHG, greenhouse gas.

effects are included in CAPRI: although the concept of the carbon tax means that the increased storage of carbon in the soil under legumes is credited to the farmer, this effect is not measured by CAPRI and thus cannot be quantified.

The net effect on average farm income would be very small, as the revenue from the tax is returned to the farming sector in the form of rewards for mitigating GHG emissions. Since some farmers will be more successful at changing their practices than others, some will benefit while others will lose out.

GM soybean imports

Nowicki *et al.* (2010) modelled several possible scenarios in CAPRI, of which the more serious one assumes that many new GM cultivars not approved for food and feed in the EU are introduced in all major soy-exporting countries. Under policies currently in force, this scenario is deemed plausible, although in recent years the industry has been responding to the demand for non-GM soy and the premium for those cultivars has reportedly come down. The scenario would lead to a cessation of soy imports from the major suppliers: the USA, Argentina and Brazil, as well as from Paraguay (a minor source). In all of these countries, the different cultivars of soy are grown in close proximity, such that the risk of traces of unapproved soy in batches of approved soy is high. Only Canada and some parts of Brazil, where GM and non-GM production areas are geographically separated, would continue to supply soybean to the EU.

The effects would be multiple and complex, but one of them would certainly be an increase in the production of soybeans as well as other legumes in Europe. Nowicki *et al.* (2010) showed that the total area under grain legumes would increase by 1 million ha, half in the form of soybeans and half in peas and faba beans, which would serve as substitutes for soybeans. This represents an increase of 67% over the reference scenario and would nullify the decline in legume area over the last 25 years or so. Production would increase even more, as the higher prices (the instrument through which farmers would be motivated to grow legumes) are also an incentive to seek increased yields. The land used for legumes would come at the expense of other arable crops, an effect made even larger because maize (of which the EU imports some 50–60 million t/year) would also be affected by the trade disruption, necessitating increased domestic production of maize for stockfeed. Even some land now under vegetables or permanent crops would be converted to growing maize and legumes.

The economic effect would be a loss to the livestock sector, against which arable farmers would gain. On balance, the agricultural sector would neither lose nor gain, although there would be a redistribution of income among different groups of farmers. Consumers would be affected by higher prices of animal products, to the tune of €10.5 billion/year across the EU.

Nowicki *et al.* (2010) do not specify the environmental impact of this scenario, but we estimate that it would be similar to the impact of the carbon tax scenario.

Discussion and Conclusions

The scenario outcomes must be seen not in comparison with today's situation, but in relation to the reference scenario. Policies prevailing in 2013 are likely to lead to further decline in legume cultivation. The question that the policy scenarios are designed to answer is whether they are able to reverse this trend.

Our analysis indicates that measures which can be included in the CAP with relative ease are unlikely to reverse the trend of declining legume cultivation in Europe. Only much bolder policies, such as an ambitious climate change strategy, could achieve that. How plausible are such scenarios, and to what extent may we trust their results?

Accepting legume cultivation as a way to fulfil the EFA obligation is the least controversial policy, since use of nitrogen-fixing crops (i.e. legumes) has been formally accepted as a permissible land use in EFAs in 2013, although member states may implement this possibility as they see fit. In the Netherlands, for instance, only perennial legumes (i.e. forage crops such as clover or lucerne (alfalfa)) are allowed. Hence, our modelling of this scenario may be regarded as a forecast of the impact of an existing policy – albeit one that is not included in the reference scenario, as it was not yet known at the time that the reference scenario was built. Yet, even this policy is not without controversy: some in the environmental policy community see it as less beneficial for the environment than the alternatives such as semi-natural vegetation. As we saw in the previous section, farmers, too, might find the option less attractive than fallow. That is why we predict its effect to be very small.

The premium per hectare for growing grain legumes is the most straightforward of our scenarios, and one that has been effective in the past. However, it goes against the trend of CAP reforms over the last 15 years, which will make it less attractive to policy-makers. To make the scenario a little more realistic, we have made the premium independent of production quantity and also set it up in such a way that the premia would be limited in terms of the amounts paid per hectare and as a percentage of total CAP payments under Pillar 1 (direct farm payments). Such a modest policy produces modest results, but a greater impact on legume production than the EFA measure, and is probably more acceptable from an environmental perspective. We predict that the declining trend of legume cultivation would be reversed into a modest upward one.

The forage legume scenario was chosen to provide a focus on this important crop group. As expected, the environmental impact is favourable, not only because of the direct effect of forage legumes on reducing fertilizer needs and nitrous oxide emissions, but also because the livestock herd is reduced, leading to reduced methane emissions. The policy comes at a cost to grassland farmers, who might of course be compensated for this if the environmental benefits are deemed sufficiently high.

Promoting a change in consumption patterns by taxing meat and subsidizing vegetable protein is attractive in that it directly addresses consumption patterns to protect the environment. It is unlikely to come to pass as a European policy, although it might be considered by individual member states; in our scenario we

have considered only the situation where such a policy would be implemented in all member states. One might have expected that if the demand for meat decreased then farmers would respond by changing their production in the desired direction. CAPRI forecasts a different outcome because trade is affected more than production. Less meat would be imported and more exported, and the opposite would apply to protein crops. The overall effect on the area dedicated to legumes would be minimal: whereas production of pulses would increase, soybean production would not. Meanwhile, the direct economic cost to both farmers and consumers would be high. We have not included a calculation of the health benefit of the change in consumption patterns, because doing so would require: (i) an estimate of the healthy life years (HLY) gained by the change; and (ii) an estimate of the monetary value of an HLY. There exists a body of literature for the latter (see, for instance, Schoeni *et al.*, 2011), but the former is highly controversial and the subject of a debate beset by ideological differences.

The carbon tax would have a large effect. The carbon tax scenario would fit into a more ambitious climate-change mitigation policy than currently pursued in the EU. Its cost in direct welfare terms would be quite substantial both to farmers and to consumers, but in the long term the benefits might well outweigh them (Kuhlman and Linderhof, 2014).

The GM scenario too would have a very significant impact, both on the livestock sector in general and on the cultivation of legumes. However, it is precisely this impact which may provoke policy makers to push for a modification of current policy on GM. The rationale behind the study from which our findings are drawn was to warn of the possible consequences of that policy.

Turning to the question of the reliability of our results rather than the plausibility of the scenario assumptions, naturally this is affected by the assumptions and limitations of the CAPRI model. For one thing, as the model does not contain parameters and data for the cultivation of crops not grown in a particular region, it cannot simulate introductions, only expansions or contractions. As the various maps show, there are only a few regions in Europe where no legumes are grown (or more correctly, where existing data do not show them). CAPRI models two types of grain legumes, soybeans and pulses, and whereas pulses are widespread, soybeans are grown only in a limited number of regions. Undoubtedly, measures to promote legumes would cause them to be grown in some regions where they are not presently grown but could be. This problem may well lead to an underestimation of the effect of all legume-promoting policies.

Compulsory forage legumes present another difficulty: CAPRI does not contain forage crops other than silage maize, although it does have data on clover in grassland. The model is also limited in that it only simulates the effect of clover on biomass quantity, not on its quality; in other words, the higher protein content of a grass-clover mix is not taken into account. Also in this case, the model yields a conservative estimate of the benefits of legumes. Moreover, a policy on forage legumes might well stimulate innovations in pasture management, such that the extra cost to farmers would be minimized or even reversed.

Financial incentives are only one way of influencing farmers' behaviour. Progress in research on legumes, and the application of this knowledge to local conditions, may well make them more attractive than they are today. Policies

promoting not only such research but also cooperation between researchers and farmers will reduce the profitability gap between legumes and alternative crops. Such policies, which we might term ‘sermons’ as opposed to ‘carrots’ (financial incentives such as the legume premium, the EFA policy, the meat tax and the carbon tax) and ‘sticks’ (regulations such as the compulsory clover-in-grassland policy), would be a departure from the focus on increasing the yield of crops such as wheat or potatoes. The effect of research and extension may be less predictable, but not necessarily smaller than the effects we are able to simulate by modelling.

Nevertheless there is undoubtedly a role for carrots and sticks as well as sermons. Concluding from our research, the most promising way to promote grain legumes would be through a policy taxing GHG emissions at a fairly high rate; that policy would not be restricted to the agricultural sector and would produce a much wider impact than analysed here. An additional policy would be needed to promote forage legumes in grassland; we have shown only one example of such a policy, but inventive policy makers may well come up with better ones. Our modelling exercise did not discuss management practices such as rotation patterns with legumes. CAPRI is not equipped to deal with them, but legume-friendly policies may well consider such aspects.

References

- Anderson, C.W. (1977) *Statecraft: Introduction to Political Choice and Judgment*. Wiley, Hoboken, New Jersey.
- Bemelmans-Videc, M.-L., Rist, R.C. and Vedung, E.O. (eds) (2003) *Carrots, Sticks and Sermons: Policy Instruments and Their Evaluation*. Transaction Publishers, Piscataway, New Jersey.
- Boatman, N.D., Parry, H.R., Bishop, J.D. and Cuthbertson, A.G.S. (2007) Impacts of agricultural change on farmland biodiversity in the UK. *Issues in Environmental Science and Technology* No. 25. Royal Society of Chemistry, London.
- Britz, W., Heckeley, T. and Kempen, M. (eds) (2007) Description of the CAPRI modelling system. Final report of the CAPRI-Dynaspat project. Institute for Food and Resource Economics, University of Bonn, Bonn, Germany.
- Dicks, L. (2014) Ecological Focus Areas: Will Planting Peas and Beans Help Bees? Lynn Dick's Blog, 10-6-2014. Available at: <http://www.valuing-nature.net/> (accessed 10 June 2014).
- Ehlers, K., Schulz, D., Balzer, F., Wogram, J., Holzmann, T., Kärcher, A., Becker, N., Klein, M., Krug, A., Jessel, B., Ribbe, L., Güthler, W., Heißenhuber, A., Hülsbergen, K.-J., von Meyer, H., Peterwitz, U. and Wiggering, H. (2014) Ecological Focus Areas – Crucial for biodiversity in the agricultural landscape! Position paper of the Umweltbundesamt, Dessau-Roßlau, and the Bundesamt für Naturschutz, Bonn, Germany, January 2014.
- European Commission (2013) Regulation (EU) No. 1307/2013 of the European Parliament and of the Council. *Official Journal of the European Union* 20-12-2013.
- Eurostat (2015) Eurostat. European Commission, Brussels. Available at: <http://ec.europa.eu/eurostat> (accessed 30 April 2015).
- FAOSTAT (2015) Statistics Database of the Food and Agriculture Organization of the United Nations. Food and Agriculture Organization of the United Nations, Rome. Available at: <http://faostat3.fao.org/home/E> (accessed 30 April 2015).
- Helming, J., Kuhlman, T., Linderhof, V. and Oudendag, D. (2014) Impacts of legume scenarios. Legume Futures Report 4.5. Available at: www.legumefutures.de (accessed 30 April 2015).

- Humphreys, J., Mihailescu, E. and Casey, A. (2012) An economic comparison of systems of dairy production based on N-fertilized grass and grass–white clover grassland in a moist maritime environment. *Grass and Forage Science* 67, 519–525.
- Kuhlman, T. and Linderhof, V. (2014) Social cost–benefit analysis of legumes in cropping-systems. Legume Futures Report 4.6. Available at: www.legumefutures.de (accessed 30 April 2015).
- Nowicki, P., Aramyan, L., Baltussen, W., Dvortsin, L., Jongeneel, R., Pérez Domínguez, I., Van Wagenberg, C., Kalaitzandonakes, N., Kaufman, J., Miller, D., Franke, L. and Meerbeek, B. (2010) Study on the implications of asynchronous GMO approvals for EU imports of animal feed products, Final Report. Agricultural Economics Research Institute, The Hague, the Netherlands/Economics and Management of Agro-bio-technology Center, University of Missouri/Plant Research Institute, Wageningen, the Netherlands.
- Schoeni, R.F., Dow, W.H., Miller, W.D. and Pamuk, E.R. (2011) The economic value of improving the health of disadvantaged Americans. *American Journal of Preventive Medicine* 40, S67–S72.
- Stern, N. (2006) *The Economics of Climate Change*. Cambridge University Press, Cambridge.
- Woltjer, G., Bezlepkina, I., Van Leeuwen, M., Helming, J., Bunte, F., Buisman, E., Luesink, H., Kruseman, G., Polman, N., Van der Veen, H. and Verwaart, T. (2011) The agricultural world in equations: an overview of the main models used at LEI. Memorandum 11-151. LEI Wageningen University, The Hague, the Netherlands.

15 Developing Legume Cropping: Looking Forward

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Europe is self-sufficient in most agricultural commodities that it can produce. It is even a net exporter of cereals. This remarkable productivity can be attributed to specialization in high-yielding cereals and oilseeds supported by synthetic nitrogen fertilizer, and large imports of soy from North and South America. However, this productivity comes at a cost for the environment linked to imbalances in European cropping systems. By 2010, when the Legume Futures project was initiated, awareness of these imbalances in our agricultural and food systems was already the subject of discussion in the mainstream agricultural policy community.

This book is the work of 58 authors from across Europe and beyond. Most have received support from the European Union (EU) for research and innovation activities that aim to support legume production. Almost all have received some form of public support. The total support certainly runs to several tens of millions of Euros. In addition to Legume Futures, the EU has invested in LEGATO, LEGRESIST, EUROLEGUME and ABSTRESS, among others. National governments have invested in projects such as CLIMATE CAFÉ, MEDILEG, REFORMA, COBRA and NORFAB. There are many other projects and more regional initiatives to support the production of legume crops in Europe.

This is all applied research. Its primary purpose is to improve the performance of farming and food systems and thereby provide benefits for people and the environment. This purpose is served when research results are used to deliver new practices, technologies, products, support organizational and institutional change, and to support evidence-based policy making. If successful, the research that the authors of this book are now doing or have recently completed will be making an impact on our farms and in our food systems in the next decade and beyond. Will we in 10 years be able to celebrate real impact from that research? Will we be able to

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proudly point to positive change commensurate with the investment our research represents and say we had a part in that?

Such change is not about promoting legumes. Legumes are neither good nor bad. Success for our research is about informing the effective rebalancing of farming and food in Europe using legumes. It is also about global change. In South America, cropping systems with more than 50% soy are common, so their cropping sequences are too simple. Europe is the second largest importer of soy from that region, including from cropping systems that few of us would regard as sustainable. At the same time, enabled by imports of soy, farmers in Europe have reduced legume production to the point that most European cropping systems do not use any legumes at all, so the system is imbalanced at field, farm, regional and global scales. But is change really needed?

Europe is more self-sufficient in protein than is commonly implied. While Europe imports about 70% of the protein-rich material used for feed supplementation, it is actually about 70% self-sufficient in tradable plant protein when all grain and arable forage protein sources are considered. This self-sufficiency estimate increases further when we take the protein from grassland into consideration. Many economists would argue that instead of regarding specialization and imports as a problem, we should celebrate them as a consequence of rational and effective exploitation of comparative advantage. European farmers are as good as or better than farmers in legume-exporting countries at growing legumes, but they are especially good at growing cereals. Agricultural land is scarce in Europe and the cost of land is high. High land rents in particular force farmers to allocate land to crops which are particularly productive in Europe, in most cases cereal crops. A textbook example of Ricardo's law of comparative advantage is clearly at work.

Can we expect change if the current situation reflects rational economic decision making by farmers and wider economic advantage that the use of comparative advantage brings? We can speculate on a number of fundamental changes that determine the likelihood of a rebalancing of agriculture supported by legumes grown in Europe. Reference to Ricardo's law in this context assumes that cropping systems are really optimized from a farm economic viewpoint. But is this the case? Chapter 13 in this volume reflects on the complexity of making assessments of the economic performance of cropping systems and shows that the real (farm-level) economic performance of legumes is higher than conventional gross margin analysis indicates. This means that the potential for economically competitive legume production is probably not fully exploited. However, even accepting that the farm-level economic performance of legume crops is often underestimated, there is consensus that there is a lack of compelling economic grounds for growing legumes for many farmers, especially where cereals and oilseeds grow particularly well. For this to change, we need a number of fundamental changes in framework conditions.

The first is that the technical performance of legume crops needs to improve compared with competing crops. In practical terms, this means that the net output of legume crops needs to grow faster than the net output of competing crops. There is some good evidence that this is possible. Cereal crop yields are stagnating even though breeding continues to increase yield potential (Brisson *et al.*, 2010). Climate change may be at least partly responsible, but negative agronomic factors related to the lack of diversity in modern cropping systems are also likely to

play a role. This conclusion is supported by practical observation with increasing problems with weeds and diseases in cereal crops in particular. This means that modern cereal-based systems are approaching and exceeding resource and environmental limits that restrain their performance. If the performance of cereals stagnates or even declines, and performance of legumes continues to increase, we will over time see the comparative advantage of cereals over legumes decline. With this, the number of situations where legumes are competitive due to agronomic reasons will increase. This scenario is supported by investment in plant breeding and improving cropping systems in particular.

The second and related possibility is the costs of producing crops that compete with legumes increases disproportionately. Humphreys *et al.* in Chapter 9, this volume, provide an example of how the price of fertilizer nitrogen influences the profitability of introducing white clover into grass-based farming. In an excellent example of combining biological and economic research, they identified a tipping point in the ratio of fertilizer nitrogen price and the farm-gate price of milk in Ireland. When the ratio of the cost of 1 kg of nitrogen to the price of 1 kg of milk exceeds about 3, grass-white clover-based production tends to be no longer economically disadvantaged. The price of synthetic nitrogen is particularly relevant to perennial systems where the recovery of biologically fixed nitrogen in the system over years is high. Perennial forage crops require large amounts of nitrogen, which can be effectively provided by introducing legumes. The scope for this effect in arable systems is somewhat lower, although clearly the attractiveness of more diverse cropping sequences increases as the cost of maintaining intensive cereal production using synthetic fertilizer nitrogen and plant protection products increases.

The third possibility is the basic value of the crop produce increases relative to that of other crops. Schätzl and Halama (2013) in Bavaria have estimated that if the farm price of soy is more than about twice that of wheat, soy is competitive with wheat in that region. This ratio depends ultimately on the base price of protein compared with starch, set mostly by the world prices for wheat, maize and soy. Long runs of commodity price data (available from Index Mundi) show that the ratio of soy to wheat prices was consistently below 1.5 between 1990 and 2009. The last 3 years (up to mid-2016) are characterized by relatively high soy prices. From Schätzl and Halama (2013), we can expect that these soy prices are high enough to make soy competitive against wheat in many parts of Europe. Reports from farms confirm this. The currently rapid growth in the demand for soy from China is an underlying driver for high soy prices. Using analysis of scenarios, Pilorge and Muel (2016) indicated that the current high prices for plant protein are here to stay, but their scenarios do not highlight the effects of further globalization and increased free trade. From their work, it is reasonable to conclude that protein remains valuable compared with carbohydrate and oil, and that this increases the potential for legumes in Europe with protein yield per hectare being a key determinant of success. Such a development will impact most on the value of produce with the highest protein concentration (soy and lupin). The high starch content of pea and faba beans means that the upward pressure on the value of their protein is buffered by the downward pressure on the relative value of the starch. However, the overall effect is that pea, faba bean and other pulses will become more competitive when protein prices rise.

The fourth possibility is that the market rewards the higher environmental performance of value chains that use legumes. There is definitely growing interest within agriculture and food in higher process quality, manifest in the rapid growth in corporate social responsibility schemes in the sector (Murphy-Bokern and Kleeman, 2015). However, for legume production in Europe to sustainably and substantially benefit from such market premiums, it must be clear that legume crops support improved environmental performance that the consumer can recognize and reward. As we can see in Chapters 3 and 4, this volume, and from Bues *et al.* (2013), there is consensus that diversifying our cropping systems using legumes will bring environmental benefits, but these benefits are modest and probably not sufficient to drive large premiums.

Transition theory offers a fifth prospect for change. In addition to the individual fundamental factors, there is also the possibility of fundamental change based on a combination of small changes leading to breakthroughs at the system level. Voisin *et al.* (2014) argued that the development of legume production has been hindered by lock-in within incumbent structures and processes. For example, older trade agreements supported specialization of EU agriculture in cereal production and this has stimulated infrastructure investment in processing large amounts of imported soybean meal. Complementing this, Europe's natural ability to produce high-yielding cereal crops was reinforced by public and private investment in cereal breeding and supporting technologies. The resulting lock-in or dominance of the incumbent system is manifest for example in the market under-valuation of pea and faba bean in relation to their nutritional contribution in compound feeds (see Chapter 13, this volume). Compared with the dominant European cereal/imported soy system, the lack of a critical mass of production of alternative legumes in Europe reduces investment in technical support and leads to higher transaction costs. With such lock-in, a self-reinforcing dynamic supporting the dominant system works parallel to a self-reinforcing dynamic that discourages alternatives, for example in different levels of research investment. Voisin *et al.* (2014) argued that starting with combining niche high-value chains that give priority to a secure and high-quality supply within regionalized systems, new broader structures and processes can be established. The theory of transition (Geels, 2011) indicates that such new systems can emerge when the effects of several niche innovators coalesce. The innovators in these niche systems are free of the constraints in the dominant system and a wide range of technical and organizational innovations can play a role in each case. Eventually the success of these niche innovations influences the dominant system and changes it. An example of this is the influence that organic food processing has had on the development of 'clean label' processing in conventional food. Voisin *et al.* (2014) argued also that new innovative value chains can target high transaction costs in the conventional system, for example the high costs of controlling the quality of internationally traded commodity compared with the lower cost of controlling the quality of locally grown crop produce. The additional advantage of 'peace of mind' that comes from having direct access to crop produce of known origin can also play a significant role in commercial decisions. New value chains may synergize with each other and with the dominant system. In animal feeding, legume species not only complement cereals, they complement each other, offering a more diverse

and resilient supply chain. In agricultural development contexts, the development of a high-value tradable crop such as soy can be used to spearhead improvement of farming more generally. This is particularly relevant in Eastern Europe where synergies based on improved cropping sequences that use legumes can increase the output of both legumes and non-legume crops. Growth of legume production in the east offers the opportunity of new east-to-west trade within Europe as an alternative to trans-Atlantic soy imports.

Lastly, the sixth approach to change is the use of public policy measures. Kuhlman *et al.* in Chapter 14, this volume, reflect on options making it clear that the development of policy instruments is not as easy as is often assumed in public debate. A range of policy instruments supporting legume production have been introduced in the last 2 years in the EU and there are early indications that the trend in the decline in the production of legumes has been reversed. However, as observed in debate recently in the European Parliament, there are trade-offs and political contraindications. There is particular caution about forfeiting the benefits of comparative advantage and the effect that using alternative protein sources might have on feed costs (assuming that alternatives are more expensive). Perhaps the dominant concern now is the challenge to European level measures in general, particularly measures under 'greening' that seek to influence farmers' decisions about the use of their land. In addition to the general 'greening' measures (crop diversification and the ecological focus areas), direct subsidy for protein crops (grain legumes and lucerne (alfalfa)) is provided by the Voluntary Coupled Support in 16 of the 28 EU countries. Payments range from €36/ha in Finland to €417/ha in Slovenia, but official statistics do not yet reflect the effects. Nevertheless, trade sources anecdotally report increased demand for seed for these crops and this generally provides short-term confidence in investment in related value chains.

The future, of course, depends on a combination of these six developments. A systematic use of value chain approaches will help combine and harness these approaches for sustained change at local level within the diverse farming and food systems across Europe. For this, the recently announced plan from the European Commission to invest in innovative research looking at the development of legume-supported value chains is very significant. Development to date provides a rich resource of practical know-how and insights embedded in farming and food businesses which can now be harnessed to improve systems supported by research-based experts. This 'multi-actor' approach complements the research we have had to date, which was largely about components of systems. The successful harnessing of this combined knowledge in value chains is the way forward if we are to be able to look back proudly at effective change in 10 years.

References

- Brisson, N., Gate, P., Gouache, D., Charmet, G., Oury, F.-X. and Hurd, F. (2010) Why are wheat yields stagnating in Europe? A comprehensive data analysis for France. *Field Crops Research* 119, 201–212.

- Bues, A., Kuhlmann, T., Lindstrom, K., Murphy-Bokern, D., Preissel, S., Reckling, M., Stoddard, F.L., Topp, K., Watson, C. and Zander, P. (2013) The environmental role of protein crops in the new Common Agricultural Policy. The European Parliament, Brussels.
- Geels, F.W. (2011) The multi-level perspective on sustainability transitions: response to seven criticisms. *Environmental Innovation and Society Transition* 1, 24–40.
- Murphy-Bokern, D. and Kleeman, L. (2015) The role of corporate social responsibility in reducing greenhouse gas emissions from agriculture and food. A study for the International Food Policy Research Institute. Available at: www.murphy-bokern.com (accessed 4 July 2016).
- Pilorge, E. and Muel, F. (2016) What vegetable oils and proteins for 2030? Would the protein fraction be the future of oil and protein crops? *Oilseeds and Fats, Crops and Lipids* 23(4), D402.
- Schätzl, R. and Halama, M. (2013) Micro-economics of soya production. Presentation to the 2012 Danube Soya Congress, Augsburg, Germany, 25–26 November 2013.
- Voisin, A.-S., Guéguen, J., Huyghe, C., Jeuffroy, M.-H., Magrini, M.-B., Meynard, J.-M., Mougel, C., Pellerin, S. and Pelzer, E. (2014) Legumes for feed, food, biomaterials and bioenergy in Europe: a review. *Agronomy for Sustainable Development* 34, 361–380.

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Legumes in Cropping Systems

Edited by **Donal Murphy-Bokern, Frederick L. Stoddard**
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Based on contributions from members of the Legumes Future research consortium and complemented by articles from other research teams, this book provides a comprehensive overview of knowledge relevant to developing legume-supported cropping systems in Europe. It reflects the growing interest in using legumes to improve cropping and the current debate over the imbalance in European farming systems where the low use of legumes has caused concern in the agricultural policy community. This book supports informed debate and decision-making that addresses the associated challenges.

Legumes in Cropping Systems presents current knowledge on this subject across 15 coordinated chapters. Each chapter addresses a specific aspect of legume cropping and provides insight into the relevant literature to help support understanding and explore the underlying processes that influence cropping system development. This book includes coverage of:

- The role of legumes in cropping systems.
- The role of legumes in European protein supplies.
- Environmental effects of grain and forage legumes.
- Current status of the major grain and forage legume crops.
- Economic effects.
- Policy development.

Written by an international team of expert authors and presented in full-colour throughout, this book is an invaluable resource for researchers in agronomy and crop sciences, agricultural professionals, policy makers, and students.

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