Perennial Clovers and Ryegrasses as Understorey Crops in Cereals

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Doctoral thesis

Swedish University of Agricultural Sciences

Uppsala 2003

Acta Universitatis Agriculturae Sueciae
Agraria 414

ISSN 1401-6249
ISBN 91-576-6439-0

Tryck: SLU Service/Repro, Uppsala 2003

Abstract

Bergkvist, G. 2003. *Perennial clovers and ryegrasses as understorey crops in cereals*. Doctor's dissertation.
ISSN 1401-6249, ISBN 91-576-6439-0

Perennial crops undersown in cereals provide ground cover from harvest of the cereal crop to sowing of the next crop. Such cover crops can *e.g.* reduce soil erosion, nutrient leaching and N fertiliser requirements of the succeeding crop. The objective of this thesis was to develop guidelines on how to prevent grain yield losses due to competition from the perennial crops or to increase the yield of the main crops. The effects of species and time of undersowing of perennial crops in spring cereals, and the management of an intercropping system in which winter oilseed rape or consecutive crops of winter wheat were established in a remaining crop of white clover, were studied.

The biomass of undersown cover crops by the time of the harvest of spring barley was significantly reduced with each delay in the undersowing, but the increase in biomass during autumn was generally not affected. Italian ryegrass (*Lolium multiflorum* Lam) and perennial ryegrass (*Lolium perenne* L.) reduced the grain yield by 6 and 1%, respectively, but may both be suitable as cover crops with the appropriate main crop, time of undersowing and seed rate. Undersown white clover (*Trifolium repens* L.)/perennial ryegrass mixtures kept soil mineral N as low as pure ryegrass and improved the residual effect. This suggests that clover in the cover crops may reduce the N fertiliser requirements of the succeeding crop without increased N leaching.

Grain yields were smaller in the wheat/clover system than with wheat alone when the wheat was direct drilled and larger when sown after stubble cultivation. Direct drilled wheat and rape yielded more with clover varieties less adapted to the cold climate than with varieties in common use in the area. Grain yield increased, weeds were efficiently controlled and the white clover crop maintained by applying herbicides that mainly act as germination inhibitors when a third consecutive wheat crop had 1–2 leaves. It was possible to conclude that (1) the tillage performed in conjunction with the sowing of wheat, (2) the weed control practice, and (3) the choice of clover variety, have large effects on the yield of the winter annuals in the intercropping system.

Keywords: *Trifolium pratense*, living mulch, catch crop, green manure, bicropping, *Triticum aestivum*, *Brassica napus*.

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Contents

Appendix

Papers I–IV

This thesis is mainly based on the following papers, which are referred to in the text by their Roman numerals.

I. Ohlander L., Bergkvist G., Stendahl F. & 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.

II. Bergkvist, G., Ohlander L. & Nilsdotter-Linde, N. Biomass and N uptake of relay cropped mixtures and pure crops of white clover and perennial ryegrass and their effect on soil mineral nitrogen and subsequent crop. (Submitted).

III. Bergkvist, G. 2003. Influence of white clover traits on biomass and yield in winter wheat- or winter oilseed rape-clover intercrops. *Biological Agriculture & Horticulture 21*, 151–164.

IV. Bergkvist, G. 2003. Effect of white clover and nitrogen availability on the grain yield of winter wheat in a three-season intercropping system. *Acta Agriculturae Scandinavica, Section B, Soil and Plant Science 53,* 97–109.

Preface

The work of Nature is free. During spring and early summer, farmers manage their crops to use that work as efficiently as possible to produce large and economic yields. However, during long periods of the year the land lies fallow or sparsely vegetated. It is my hope that the results of my research will help farmers to use the work of Nature during the fallow periods to reduce the need for purchased goods and services. This would help farmers to make their production more efficient in terms of resource use and more independent of agribusiness and political decisions.

I started my research studies at SLU in the Faculty research theme "Resource Efficient Agricultural and Horticultural Systems" in the spring of 1995. Wes Jackson at The Land Institute in Salina, Kansas, and Howard T. Odum at the University of Florida in Gainsville, Florida, were my main sources of inspiration.

Jackson (1985) presented ideas and arguments for an agriculture based on the way Nature works. The American prairie was the model. The fertility of the soils on the American prairie, which has been formed over thousands of years, rapidly declined after the prairie was ploughed and cropped with annual crops. Public awareness of this was awakened in the 1930s when wind erosion led to the famous "Dust bowl". The natural prairie consists mainly of perennial species of cool and warm season grasses, legumes and composites, differing in nutrient requirements and seasonal resource use. The idea of Jackson (1985) was to develop an agroecosystem with the same functional groups. The aim was, and still is, to develop a system that produces harvestable yields at about the same level as in conventional agriculture, but that mimic the soil-retaining and soil-building traits of the prairie. The system was outlined and its feasibility described by Soule & Piper (1992). Jackson (2002) summarized the history of soil degradation, the role of The Land Institute and current research at The Land Institute.

It is difficult to produce large amounts of human food in the natural forest ecosystems in Sweden. Forest fires occurred in a forest ecosystem in Finland at average intervals of 85 years without human influence (Pitkanen & Huttunen, 1999). Slash and burn agriculture can, therefore, be considered to be an adaptation of agriculture to the natural ecosystem in the Nordic countries, but cannot be expected to support the present human population (Emanuelsson, 1988). A harvest index of 10% or less, compared to about 50% with annual cereals, is what can be expected in agroforest systems (Ewel, 1999). I, therefore, restricted my ambitions to making the present agricultural systems slightly more perennial in their character rather than to mimicking the Swedish forest ecosystems. According to Ewel (1999), it is in the humid tropical lowlands that it pays best to imitate natural ecosystems, rather than to aim for simplicity. Continuous growing of annual crops in the wet tropics requires massive subsidies of pesticides and fertilisers. The best return on investment in high-technology agriculture can be expected on fertile soils in a climate that is neither too dry nor too wet, because the sum of biotic and abiotic stress is lowest on such soils (Ewel, 1999). Thus the investment can be used to facilitate the conversion of solar energy into the desired product rather than to alleviate constraints such as water deficits or pests. Other situations where investment can pay off well is when overwhelming biotic stress can be alleviated by increasing the abiotic stress, *e.g.* the flooding of rice, or when severe abiotic stress can be alleviated by using surrounding land, *e.g.* collecting water in the surrounding mountains and using it to irrigate the cultivated land in the valleys (Ewel, 1999).

When comparing the efficiency of processes, all inputs need to be compared using the same units of measurement or assessment. My second main source of inspiration and the main source of inspiration to the whole faculty research theme, Odum (1987; 1996), calculates both the direct input of renewable and non-renewable resources and the input of human goods and services as the amount of solar energy that is needed to produce the input. Thus the size of all inputs is expressed as "solar energy joules". According to Odum (1996) the process that has the lowest ratio of inputs from the economy to inputs from local renewable and non-renewable resources uses inputs from the economy most efficiently. In economies characterized by large energy flows, *i.e.* in industrialised economies, the ratio is higher than in low-energy economies, *i.e.* less industrialised economies. In order to be efficient in terms of use of resources from the economy, agriculture must be adapted to the surrounding economy. Efforts to make an efficient use of some renewable resource may very well lead to an inefficient use of other resources such as labour, machinery, pesticides, fertilisers, fertility *etc.* I wanted to introduce ecological functions into an agricultural system that was reasonably well adapted to the surrounding economy and that would lower the ratio of inputs from the economy to the inputs from local resources with maintained or improved fertility of the soil. Thus, I wanted to find management methods that were more efficient in the use of purchased goods and services compared to methods used in current conventional agriculture. I refrained from comparing resource use efficiencies between systems in the thesis, because I considered the systems to be under development.

As I see it, differences in the definition of the word efficient are the agroecological cause of much of the confusing debate between representatives of conventional and organic farming in Sweden. As I understand it, conventional agriculture in this context means an industrial agriculture that aims to make efficient use of renewable and non-renewable resources at the global scale without considering future needs that are not anticipated by the economic system. Organic agriculture is guided by ecological principles and aims to make efficient use of local resources and to increase productivity of the local ecosystem. In practice, organic agriculture adapts to the surrounding economic system, by accepting subsidies and external inputs that greatly increase the economic and energetic efficiency of the system, such as iron, technical equipment, fossil fuel and information, but do not accept the less powerful, but more controversial inputs, such as pesticides and mineral fertilisers. Organic agriculture, therefore, in practice becomes an industrialised agriculture. Anything else is difficult in an industrial economy. The degree of industrialisation differs and depends on how well the farmer uses the local renewable resources. Easily soluble mineral fertilisers and synthetically produced pesticides are the inputs that mainly differentiate the two systems. They are likely to help to make the resource use on field level more efficient in terms of transforming sunlight into food, but may also allow inefficient use of the work of Nature by alleviating the need for *e.g.* ecologically sound crop sequences, a balanced density of producing animals and the work of soil organisms and predators. The use of mineral fertilisers and pesticides may, therefore, feedback to further increase the need for inputs. It should be noted that when soils become depleted of nutrients or when pests cause severe yield losses, mineral fertilisers and pesticides are very powerful. When it happens on a large scale that nutrients become depleted or some severe pest or disease causes dramatic yield losses, practical organic agriculture could adapt to the surrounding economy and allow mineral fertilisers and pesticides in some forms. This could be done without contradicting the goals of organic agriculture as described in the proceedings from a Nordic IFOAM meeting in 1989 (IFOAM, 1989). The acceptance of pesticides would, however, surely create market challenges. The scale of problems with pests, diseases and fertility may, however, be reduced if agricultural production can be made more resilient by increasing the functional diversity in landscape, fields and species composition (Levin, 1998; Peterson *et al*., 1998; Altieri, 1999; Landis *et al*., 2000). It should also be noted that organic agriculture as defined by IFOAM (1989), apart from goals related to agroecology, also has goals on global justice, profitability, ethics and communication between producers and consumers. In order for the agriculture to become more ecological in its traits, it would help immensely if the infrastructure and the economy of the whole society were to become more guided by ecological principles than at present.

As an undergraduate student and in the year after my graduation in December 1993, I assisted Lars Ohlander at the Department of Crop Production Science at SLU in his research on the management of catch crops undersown in spring cereals (Bergkvist *et al*., 1995; Nilsdotter-Linde *et al*., 1995; Ohlander & Bergkvist, 1995; Ohlander *et al*., 1996). I used results from those early studies when writing Papers I and II in the present thesis. In 1995, 1996 and 1997 I started experiments on the management of white clover as a perennial understorey crop in winter wheat and winter rape. I present results from those experiments in Papers III and IV and in Complement I and II in the present thesis. I originally intended the system for agricultural land in densely populated areas, where, in a more ecologically based society than the present, there would be little room for animals other than humans. In the waiting for a more ecologically based economy, I hope my research will contribute towards improved efficiency in the use of the work of Nature in current agriculture.

Introduction

Definitions

Perennial clovers (*Trifolium* spp.) and ryegrasses (*Lolium* spp.), have traditionally been relay cropped in cereals as a way to establish pastures and leys (Charles, 1958; Kornher, 1970). Environmental concerns have encouraged the development of practices that require less use of chemicals and mineral fertiliser and/or that conserve soil fertility. Such practices often include perennial or annual crops grown with the purpose of assisting in the maintenance of the main crop and soil. Crops included in this manner are often called cover, catch or green manure crops depending on their intended main function. Hartwig & Ammon (2002) define a cover crop as “any living ground cover that is planted into or after a main crop and then commonly killed before the next crop is planted”, *cf.* the Swedish “mellangröda” and the German “Zwischenfrucht”. The word “cover” refers to its use as a cover to protect the soil from the destructive and eroding forces of wind and water (Langdale *et al*., 1991). Traditionally, a cover crop is a crop that establishes rapidly, *i.e.* cereals or annual forage crops, and that is sown simultaneously with a slower establishing crop, *i.e.* perennial forage crops (Charles, 1958). The protective purpose of such a cover crop is to prevent the slower establishing crop from becoming infested with weeds and to protect the soil surface from wind and water before the slow establishing crop covers the ground. Thus, the meaning of the word has drifted slightly. The main purpose of relay cropping pastures and leys with cover crops is, however, often not to cover, but to improve the economic return by being able to market the cover crop (Charles, 1958).

Catch crops and green manure crops can be synonymous with cover crop as described by Hartwig & Ammon (2002), but can also be used to define other crops grown for the same purpose. The term catch crop is sometimes used when the main purpose of growing the crop is to prevent nutrient leaching (Karlsson-Strese *et al*., 1996) and green manure crop when the main purpose is to achieve agronomic benefits (Macrae & Mehuys, 1985), such as the provision of nutrients, mainly nitrogen, to the succeeding crop.

Living mulches are cover crops planted either before or with a main crop and maintained as a living ground cover throughout the growing season or longer (Hartwig & Ammon, 2002). I use the term understorey crop to describe cover crops or living mulches growing beneath the main crop canopy. Contrary to the definition by Hartwig & Ammon (2002), I do not consider perennial crops sown in connection with fast establishing cereals as living mulches, but as cover crops, because their biomass at the harvest of the cereal is usually small (Jensen, 1991; Kvist, 1992; Bergkvist *et al*., 1995; Nilsdotter-Linde *et al*., 1995). The distinction between cover crops and living mulches made by Hartwig & Ammon (2002) applies better to perennial crops sown in slow establishing main crops, such as maize and sugar beet (*cf.* Bergkvist & Clements, 2002).

The effect of cover crops

The use of cover crops has been shown to reduce water runoff and with that, the amount of eroded soil and pesticides (Hall *et al*., 1984; Pisa *et al*., 1994; Rüttimann, 2001). Organic substances that are formed when the organic matter in the cover crops decomposes promote aggregate formation and stabilisation (Breland, 1995). The soil cover prevents raindrops from damaging soil aggregates at the soil surface (Bruce *et al*., 1992). The use of cover crops, therefore, increases water infiltration (Smeltekop *et al*., 2002) and improves soil structure (Macrae & Mehuys, 1985). Decomposing cover crops, which cover the soil surface, conserve water by decreasing the evaporation from the soil (Clark *et al*., 1997a). Cover crop residues become food for earthworms and thus earthworm populations are higher in cropping systems with cover crops or living mulches than in systems without (Buckerfield & Webster, 1996; Schmidt *et al*., 2001). Earthworm activity in itself can improve aggregate stability (Ketterings *et al*., 1997) and improve soil aeration and root penetration by increasing the number of macro pores (Logsdon & Linden, 1992). Other uses of cover crops that have been more in focus lately are as a means to control weeds (White *et al*.,1989; Hall & Hartwig, 1990; Heyland & Merkelbach, 1991; Ilnicki & Enache, 1992; Kvist, 1992; Brandsæter & Netland, 1999; Fisk *et al*., 2001; Bergkvist *et al*., 2002) and to reduce the incidence and damage caused by insect pests (Bugg & Waddington, 1994; Costello. & Altieri, 1995). In many places, its old use as a green manure crop to the fertilisation of the subsequent crop and its use as a catch crop for nitrogen to reduce nutrient leaching to surface and ground waters have received a lot of attention in recent decades. Erosion control and soil fertility conservation are probably the most common reasons for growing cover crops world wide, but in the Nordic countries its functions as green manure and as a catch crop are probably the most appreciated.

Cover crops as nitrogen supplier

N-fixing legumes are the most common green manure crops. Winter annual legumes intersown without incorporation before harvest or direct drilled after the harvest of a summer crop can supply a great deal of the N requirements of the subsequent crop. In areas with long vegetation periods, the cover crops can be sown after any summer crop. Thus in experiments performed in Georgia, U.S.A., hairy vetch (*Vicia villosa* Roth), crimson clover (*Trifolium incarnatum* L.) and subterranean clover (*Trifolium subterraneum* L.), sown in October–November, supplied the succeeding crop of grain sorghum (*Sorghum bicolour* (L.) Moench) with, on average, 72 kg N ha^{-1}, which was enough to cover its needs (Hargrove, 1986). Hairy vetch and crimson clover replaced, on average, 123 and 99 kg ha^{-1} of fertiliser N respectively, in a succeeding maize crop in investigations in Missouri, U.S.A (McVay *et al*., 1989). Similar findings were made by *e.g.* Holderbaum *et al*. (1990) and Clark *et al*. (1997b). Further north, winter annual legumes need to be sown earlier to survive winter and produce adequate amounts of N (Abdin *et al*., 1998; Vyn *et al*., 2000; Griffin *et al*., 2000). Their biomass late in autumn is often small and after a dormant period during winter they have most of their growth in the weeks before flowering in spring (Griffin *et al*., 2000). In order to produce large biomasses they must, therefore, not be incorporated until quite late in spring (Vaughan & Evanylo, 1998). Thus only crops suited to late planting are suitable for winter annual legume cover crops. In the Nordic countries the winter annual legumes should be sown in July to have the best chance of surviving the winter (Brandsæter & Netland, 1999). According to Brandsæter & Netaland (1999), the chances of survival are better with hairy vetch than with crimson clover or subterranean clover.

In areas with relatively short vegetation periods, the cover crops are often relay cropped in *e.g.* maize (Scott *et al*., 1987; Abdin *et al*., 1998), sunflower (Kandel *et al*., 2000), winter wheat (Heyland & Merkelbach, 1991; von Schultheiss & von Boberfeld, 1994; Schröder *et al*., 1997; Bergkvist *et al*., 2002), spring wheat (Garand *et al*., 2001) or spring barley (Kvist, 1992; Wallgren &. Lindén, 1994; Breland, 1996). Perennial legumes can be undersown in spring without flowering during summer and without severely reducing the yield of the main crop (Hartl, 1989; Heyland & Merkelbach, 1991; Kvist, 1992; Wallgren & Lindén, 1994; Abdin *et al*., 1998). They are, therefore, more suitable in relay cropping systems than are annual legumes. Relay cropped red clover (*Trifolium pratense* L.) or white clover (*Trifolium repens* L.) have been shown to contribute up to 90 kg ha^{-1} N to the subsequent crop (Wallgren & Linden, 1994; Breland, 1996; Schröder *et al*., 1997; Garand *et al*., 2001).

Cover crops as catch crops for nitrogen

Non-leguminous cover crops have reduced nitrogen leaching from arable land effectively in investigations carried out in many parts of the world (Martinez & Guirand, 1990; Maidl *et al*., 1991; McCracken *et al*. 1994; Davies *et al*., 1996; Francis *et al*., 1998; Shepherd, 1999). It can, however, be difficult achieve substantial growth of the cover crops in the autumn if the soil is dry at establishment (Catt *et al*., 1992) or if the cover crops cannot be sown until too late in the autumn (Rasmusen & Andersen, 1991). These problems can be avoided by undersowing the cover crops in the spring. Italian ryegrass (*Lolium multiflorum* Lam.) or perennial ryegrass *(Lolium perenne* L.) undersown in the spring in spring cereals have reduced N leaching in the following autumn and winter by about 50% in many studies (Thomsen *et al*., 1993; Lewan, 1994; Hansen & Djurhuus, 1997; Aronsson & Torstensson, 1998; Torstensson & Aronsson, 2000). Undersown grasses can have both positive and negative effects on the grain yield of the succeeding crop (Jensen, 1991; Allison *et al*., 1998; Thorup-Kristensen & Nielsen, 1998). The residual effect can be improved by mixing grasses and legumes (Wallgren & Lindén, 1994; Lyngstad & Børresen, 1996; Ranells & Wagger, 1997; Kuo & Jellum, 2002). Spring incorporation of cover crops on clayey soils can be detrimental to soil structure and result in poor synchronization of the availability of nitrogen with the needs of the main crop (Catt *et al*., 1992; Thorup-Kristensen, 1993; Catt *et al*., 1998; Thorup-Kristensen & Nielsen, 1998). This problem can largely be overcome by incorporating the cover crop in the autumn or in the winter (Thorup-Kristensen & Nielsen, 1998; Stenberg *et al*., 1999).

The undersowing of cover crops in spring cereals

It is well known that the effect of undersown crops on the main crop yield can be reduced by reducing the seed rate of the undersown crop, by delaying the undersowing in relation to the sowing of the main crop, by increasing the seed rate of the main crop and by using suitable species combinations (Charles, 1958; Kvist, 1992). Many authors have also studied the requirements of the undersown crop (Kornher, 1970, Meijer, 1987) and the effect of establishment method on the performance of the ley (Frankow-Lindberg & Kornher, 1982). Few researchers have, however, related management practices to the increase in cover crop biomass during autumn and the effect on main crop grain yield. Andersen & Olsen (1993) have shown that perennial ryegrass has a smaller effect on the grain yield of spring barley than Italian ryegrass. Kvist (1992) and Bergkvist *et al.* (1995) showed that seed rates as small as 3 kg ha^{-1} of perennial ryegrass could be used, when undersowing under suitable growing conditions in spring barley, without achieving a smaller increase in the cover crop biomass during autumn than with larger seed rates. Generally, a larger seed rate is needed with delayed undersowing than with sowing in connection with the sowing of barley (Bergkvist *et al.*, 1995). Schröder *et al.* (1997) showed that precipitation during summer correlated positively with cover crop biomass in autumn. Lyngstad & Børresen (1996) found that mixtures of white clover and grass produce more cover crop dry matter than pure grass at low N-levels, but not at high. The sowing method has had variable effects on the establishment and increase in the cover crop biomass during autumn, but, generally, the cover crop produce more dry matter when seeds are well covered with soil than when placed with little or no soil cover (Bergkvist *et al.*, 1995; Känkänen *et al.*, 2001).

Living mulches

The advantages of not killing the mulch are that more biomass can be produced, the soil surface is protected and weeds are suppressed during the whole year, the cost of establishment is reduced and problems with pests and diseases may also be decreased (White & Scott, 1991). Water and N are the main competitive factors when growing understorey crops (Hartwig & Ammon, 2002). Therefore, water consuming living mulches are best suited to moist regions. The suppression of the clover growth by mechanical or chemical means reduces its competitive effect (Grubinger & Minotti, 1990; Williams & Hayes, 1991; Thorsted *et al.*, 2002).

Living mulches are used in vineyards and orchards (Buckerfield & Webster 1996; Neilsen & Hogue, 2000), but legumes have also been introduced as living mulches in annual crops. There are published results of the use of *e.g.* crown vetch (*Coronilla varia* L.) (Hall & Hartwig, 1990) subterranean cover (Ilnicki & Enache, 1992), hairy vetch (Teasdale, 1993) or lucerne (*Medicago sativa* L.) (Eberlein *et al.*, 1992) as a living mulch in maize. White & Scott (1991) used red clover or lucerne as a living mulch in winter wheat. The legume that probably has generated the largest interest as a living mulch is, however, white clover (Bergkvist & Clements, 2002). There are reports on white clover being used as a living mulch in e.g. sweet maize (Vrabel, 1983; Grubinger & Minotti, 1990; Fischer & Burrill, 1993), maize (Echtenkamp & Moomaw, 1989; Ammon, 1994), rice (Fukuoka, 1985) winter wheat (White & Scott, 1991; Jones & Clements, 1993; Clements, 1998), spring wheat (Jones & Clements, 1993), spring barley (Williams & Hayes, 1991; Jones, 1992) and oats (Williams & Hayes, 1991; Jones, 1992; Thorsted *et al.*, 2002).

The winter wheat–white clover intercropping system

Jones & Clements (1993) showed that winter cereals were better suited to intercropping with white clover than spring cereals, because the white clover competes strongly with spring cereals. Low winter temperatures generally benefit grasses in relation to white clover (Wachendorf *et al*., 2001). According to Clements & Donaldson (1997) the winter wheat–white clover intercropping system should be managed as follows. Initially a sward of pure white clover is established. The clover should either be defoliated by machine or grazed by sheep before sowing the winter wheat. The winter wheat is then direct drilled into the white clover. A small amount of N is applied to the wheat in the spring. The crop can be harvested as whole crop silage or be left to mature and harvested for grain. The white clover recovers quickly after the harvest of the cereal and is then harvested for silage or grazed before another crop of winter wheat is direct drilled into the remaining crop of white clover.

The need for agrochemicals was found to be smaller in the intercropping system than in the conventional system (Clements & Donaldson, 1997). The dense clover canopy made it difficult for dicotyledonous weeds to survive, aphids caused fewer problems and the incidence of some splash-borne diseases (*e.g. Septoria* spp.) was less severe (Clements & Donaldson, 1997). Clover intercropped with wheat reduced the dispersal of *Septoria tritici* pycnidiospores (Bannon & Cook, 1998) and *Pseudocercosporella herpotrichoides* spores (Soleimani *et al*., 1996) compared to wheat alone in simulated rain. White clover did not reduce eyespot incidence in the field, but reduced the severity of eyespot in experiments by Soleimani *et al*. (1995). In experiments by Soleimani & Deadman (1999) populations of *P. herpotrichoides* and *Fusarium* spp. were larger on debris in plots in an intercropping system with white clover and wheat than in wheat alone. The debris in the intercropped plots did, however, decompose faster than the debris in the plots with wheat alone. Therefore the availability of inoculum lasted longer without clover in the debris. Populations of earthworms (Schmidt & Curry, 2001; Schmidt *et al*., 2001), staphylinid beetles and linyphiid spiders (Clements *et al*., 1999) were found to be larger with a perennial white clover understorey than without. The populations of earthworms were more comparable to grassland habitats than to arable land in the experiments by Schmidt *et al*., 2001). The grain yield was, however, generally substantially smaller than in conventional systems, but with less N applied (Clements & Donaldson, 1997; Clements, 1998).

Objectives

The main objective of this thesis was to develop guidelines on how to increase the efficiency in the use of perennial crops as understorey crops in cereals, *i.e.* to prevent yield losses due to competition from the perennial crops or to increase the economic yield of the main crops. The aim of the management methods was to achieve little biomass production of the perennial crops when main crops are sensitive to competition and large biomass production when competition was not assumed to severely restrict the economic yield. In practice, that often means little growth in spring and early summer and vigorous growth during late summer and autumn. The focuses and objectives of the specific studies are presented below.

Papers I–IV

In Paper I, the focus was on the effect of relay cropped Italian ryegrass, perennial ryegrass and red clover on the grain yield of spring barley and on the biomass production of the undersown crops during summer and autumn. The intended use of the undersown crops was as catch crops for nitrogen to reduce nitrogen leaching or to accumulate nitrogen during autumn to the benefit of subsequent crops. The objective was to test the hypothesis that delaying the undersowing in relation to the sowing of the main crop would reduce the yield depression in the main crop, and yet maintain the desired function of the perennial crop, *i.e.*, to grow well and thus accumulate nitrogen efficiently in the autumn. The objective was tested over three years, at two sites and with three species. In two years it was also tested at two rates of N-fertiliser.

In Paper II, the effect of relay cropped white clover and perennial ryegrass, pure and in mixtures, on soil mineral nitrogen (SMN) and on the subsequent crop was investigated. The intended use of the perennial crop was again as a catch crop for nitrogen to reduce nitrogen leaching. The purpose of including white clover was to improve the residual effect of the catch crop. The objectives of the work were to: (1) assess the biomass production and N content of relay cropped mixtures and sole crops of perennial ryegrass and white clover; (2) evaluate the possibility of replacing some perennial ryegrass by white clover without reducing the ability of the cover crop to deplete the soil profile of soil mineral nitrogen during autumn and to keep it low during winter; and (3) determine the effect of the cover crop seed mixture and time of incorporation on the yield and nitrogen utilisation by a subsequent unfertilised crop of spring barley. The objectives (1)–(3) were evaluated in three environments.

In Paper III, the effect of clover variety in a winter annual–white clover intercropping system was studied. Winter oilseed rape or consecutive crops of winter wheat were established in white clover. The white clover was undersown in spring barley in the spring before the start of the experiments. The main purpose of introducing white clover as an understorey crop in winter annuals was to supply the annual crop with nitrogen. The objective with this study was to determine whether differences in white clover traits could significantly influence the effect of a white clover understorey crop on the mature yield of intercropped winter wheat or winter oilseed rape. A well-adapted white clover variety with medium sized leaves (Sonja) was compared with one small leafed variety with good winter hardiness in the south Swedish environment (S184) and one small leafed, but less winter hardy, variety (AberCrest).

Paper IV deals with the same winter wheat–white clover intercropping system as in Paper III. One objective with this investigation was to test the hypotheses that: (1) winter wheat yields more grain over two consecutive seasons in systems with white clover than in systems without at the same rate of N fertiliser; (2) the grain yield of winter wheat can be increased by causing damage to the white clover in the autumn or in the spring; and (3) the N concentration in the kernels is higher in systems with white clover than in systems without. Another objective was to determine how the grain yield response to N fertiliser could be affected by the presence of clover and by causing damage to the clover.

Complementary study I — Establishment of winter wheat in a white clover crop

In the first year with winter annuals in the experiments presented in Papers III and IV, the grain yields were smaller in systems with white clover than in systems without. It was concluded that the competition from the clover became too strong when the winter annual was direct drilled into the white clover understorey. The objective of this investigation was to test the hypothesis that the grain yield of winter wheat can be increased and the white clover crop maintained by cultivating once before sowing the wheat.

Complementary study II — Herbicides to reduce weed pressure in a winter wheat–white clover intercropping system.

Some of the experiments used in Papers III and IV became heavily infested with weeds, particularly grass weeds. Therefore a new experiment was started in one of the experimental areas that were used in Paper IV, with the objective of investigating the effect of herbicides on wheat, white clover and weeds. It was assumed that since the white clover was already established it should not be as sensitive as the annual weeds to herbicides that mainly act as germination inhibitors. The hypotheses tested were that autumn applied herbicides that mainly act as germination inhibitors: (1) control annual weeds efficiently; (2) increase grain yield; and (3) that white clover after a herbicide treatment can reassume almost total ground cover by the time of sowing the next crop of winter wheat.

The complementary studies are referred to in the following sections of the thesis as Complement I and Complement II.

Materials and methods

Materials and methods concerning the investigations presented in Papers I–IV are briefly described below and more thoroughly described in the respective papers. Materials and methods used in Complements I–II are presented below. Brief information about the experimental sites is presented in Table 1.

Paper I

Field experiments with crops undersown in spring barley were carried out 1988–1990 at Säby and at Tönnersa (Table 1). The experiments were arranged in two- or three-factorial randomised complete blocks, with crop, time of undersowing and N-fertiliser rate as the factors. Italian ryegrass, perennial ryegrass and red clover were undersown at four development stages (Zadoks *et al*., 1974; Tottman, 1987) of the barley.

DC00: kernels still dry.
DC05: roots emerged from kernel.
DC09: first leaf at the top of the coleoptile.
DC13: three leaves fully developed.

In the four experiments carried out in 1988 and 1989, two levels of nitrogen fertiliser, 40 and 80 kg N ha^{-1}, were included, but in 1990 the lower fertiliser rate was excluded. The seed rates of the ryegrasses and red clover were 18 and 10 kg ha^{-1}, respectively. Dry matter of perennial crops in connection with the harvest of barley and late in autumn, grain yield and content of N in the perennial crops were the most important variables measured.

Paper II

Field experiments were carried out during 1992/1993 and 1993/1994 at Mellby and 1993/1994 at Lanna (Table 1). The experiments were arranged in two-factorial randomised complete blocks with crop composition and time of incorporation as the factors. Perennial ryegrass and white clover in pure stands and in two mixtures were undersown in oats, receiving 80 kg N ha^{-1}. The seed rates were chosen as a replacement series with 8 and 4 kg ha^{-1} perennial ryegrass and white clover, respectively, in the pure crop. The ryegrass:clover seed rates were defined as percent of seed rate in the pure crops. The seed rates included were 0:0, *i.e.* weeds and volunteer cereals only, 100:0, 80:20, 60:40 and 0:100. The cover crops were either incorporated by mouldboard ploughing late in autumn as one tillage treatment or were mouldboard ploughed or sprayed with glyphosate in spring as the second tillage treatment. The residual effect was measured in spring barley. The most important variables measured were the botanical composition in terms of dry matter in connection with the harvest of oats, before ploughing late in autumn and in spring, the SMN on the same occasions as the crop samplings in the first season and before sowing of barley and when the barley reached DC85 in the

Table 1. *Brief description of experimental sites used in the investigations presented in Papers I–IV and Complements I–II*

Site	Thirty year annual means		Soil texture[1]	Paper (P) Complement (C)
	Temp-erature (°C)	Precipi-tation (mm)		
Lönnstorp 55°4'N, 13°7'E	7.9[2]	655[2]	Sandy loam	P III, IV, C II
Mellby 56°3'N, 13°0'E	7.2[3]	803[3]	Loamy sand	P II
Tönnersa 56°3'N, 12°6'E	7.2[3]	803[3]	Loamy sand	P I
Lanna 58°2'N, 13°8'E	6.0[4]	558[4]	Silty clay loam	P II, IV
Logården 58°2'N, 12°4'E	6.0[4]	558[4]	Silty clay	C I
Säby 59°5'N, 17°4'E	5.3[5]	565[5]	Silt loam	P I

[1] Classification of soil particle size according to the International Society of Soil Science.
[2] Lund (SMHI). [3] Halmstad (SMHI). [4]Lanna (SLU). [5] Ultuna (SLU)

second season, grain yield of oats and barley and the N content in the perennial crops and in the barley.

Paper III

During 1995–1998, two field experiments were carried out at Lönnstorp (Table 1). In both experiments, three varieties of white clover differing in winter hardiness and leaf size were undersown in spring barley. Three consecutive crops of winter wheat followed the barley in one experiment and one crop of winter oilseed rape followed the barley in the other experiment. The white clover remained during the whole experimental period. The experiments were arranged in split-plot designs. Two densities of winter wheat and winter oilseed rape in the two experiments, respectively, were assigned to the main plots and the white clover varieties to the split-plots. Wheat and rape received 60 kg N ha^{-1} as nitrate in the spring. The first wheat crop and the rape were sown without previous tillage, but the second and third wheat crops were sown after cultivation of the stubble to reduce competition from the white clover. Botanical dry matter composition late in autumn and at flowering of the wheat and grain/seed yield were the most important variables measured.

Paper IV

Field experiments were started at Lönnstorp in 1995 and at Lanna in 1996 with the undersowing of white clover in spring barley. Two consecutive crops of winter wheat, which were direct drilled or sown after stubble cultivation in the first and second year, respectively, followed the barley. The experiments were two-factorial and arranged in strip-plot designs (Gomez & Gomez, 1984). Cropping system constituted the first factor and the application of 0, 50 or 100 kg ha^{-1} or 0, 40, 80 and 120 kg ha^{-1} of N as nitrate to the winter wheat at Lönnstorp and Lanna, respectively, constituted the second factor. The cropping systems were reduced tillage systems: (1) without white clover; (2) with white clover; (3) with herbicide treated white clover. In the herbicide treatment, the standing biomass and growth of white clover were reduced by applying tribenuronmethyl about two weeks before the expected start of stem elongation of the wheat. At Lanna, the reduced tillage systems were compared with (4) a conventional system, in which ploughing and harrowing were carried out before sowing of winter wheat (PH). Spring harrowed systems, with and without mowing of white clover at the emergence of wheat, were included at Lönnstorp and spring harrowed systems, with and without white clover, were included at Lanna. The results of those systems are not presented and only briefly discussed in Paper IV. Those treatments did not notably affect grain yield and were excluded to increase clarity in the presentation of the data. Botanical dry matter composition late in autumn and at flowering of the wheat, grain yield, yield components, N content in wheat and SMN were the most important variables measured.

Complement I

The experiment was started in the summer of 1997 at Logården (Table 1), which is an experimental farm operated by the Agricultural Society of Skaraborg (described by Helander, 2002). Winter wheat was established in an existing green manure crop that was relay cropped in oats in 1996. The green manure crop consisted of a mixture of perennial ryegrass and white clover. The experimental area was treated with a graminicide on June 19, 1997 to achieve a pure stand of white clover.

The experiment was arranged in a randomised complete block design with the method of wheat establishment as the sole experimental factor. The winter wheat was sown (1) without previous tillage and with mowing of the white clover three days after sowing of the wheat, (2) after one tillage operation with a cultivator with spring tines (Väderstad AB, Sweden) or (3) after one tillage operation with a cultivator with goose foot tines (Wibergs AB, Sweden). The sowing was carried out with a Väderstad Rapid (Väderstad AB, Sweden), which is a universal seed drill with single disc coulters followed by rubber press wheels. The sowing in treatment (1) and the tillage in treatments (2) and (3) were carried out on September 12 and the sowing in treatments (2) and (3) was carried out on September 16. No fertilisers or chemicals were applied during the experimental period.

The establishment was evaluated by counting the number of wheat plants on 2*1 row metres in each plot in late October and in early April. The number of ears m^{-2} and the dry matter of shoots of wheat, white clover and weeds on August 12 (DC85; according to Tottman, 1997) were determined from 0.5 m^2 samples cut at ground level in each plot. The dry matter grain yield was determined from 24 m^2 areas harvested on September 21. Data were treated statistically using procedure GLM in SAS (SAS Institute, 1990).

Complement II

The experiment was started in the autumn of 1997 at Lönnstorp on the same experimental area that during 1995–1997 was used in the experiment reported on in Paper IV. The experimental area was stubble cultivated with a spring tine cultivator (Väderstad AB, Sweden) on September 9 in 1997 and was two days later sown with winter wheat c.v. Ritmo using a Väderstad Rapid seed drill. The weeds were controlled with different mixtures of isoproturon and diflufenican according to Table 2 as the new experimental treatments. The herbicides were applied perpendicular to the previous cropping system treatments and included 6m * 6m in each cropping system. The herbicide treatments were randomised to the plots in the first replicate. The second replicate was not used due to an error in the fertilising procedure in the second crop of wheat. In the third and fourth replicates, the herbicide treatments were randomised to the plots with the restriction that each herbicide treatment could only occur once in each of the previous fertiliser levels. This third wheat crop was fertilised with sufficient amounts of P and K and with 60 kg N ha^{-1} as nitrate by the start of stem elongation (DC30).

The dry matter botanical composition of shoots on 4 * 0.25 m^2 in each plot was determined at flowering of wheat, 23–26 June. One sub-sample was taken on a representative site in each of the previous cropping system treatments, except in one of the two systems that included spring harrowing. The winter wheat was harvested and the dry matter grain yield determined from 44.8 m^2 in each plot on August 20. The total N concentration in the kernels was determined on an auto analyser (Leco, CN 2000, USA) using dry combustion according to the Dumas method. The white clover ground cover was estimated when it was considered suitable to start preparing for the sowing of a fourth consecutive crop of winter wheat, *i.e.* on September 9, 1998. No fourth crop was sown. Data were subjected to analyses of variance in accordance with a randomised complete block design using procedure GLM in SAS (SAS Institute, 1990). The effect of previous treatments and the restrictions in the randomisation are not considered in the statistical analyses presented in this thesis.

Results and discussion

Perennial clovers and ryegrasses as cover crops

Biomass and N uptake

Species

Undersown Italian ryegrass, perennial ryegrass and red clover reduced the grain yield of spring barley by, on average, 6, 1 and 5 %, respectively (Paper I). The differences were not significant (P = 0.07), but similar differences in the effect of Italian and perennial ryegrass on the grain yield of spring barley have been found

Table 2. *Chemical weed control treatments in a third consecutive crop of winter wheat sown in white clover living mulch at Lönnstorp*

Treatment	Isoproturon ($g\ ha^{-1}$)	Diflufenican ($g\ ha^{-1}$)	Time of application
A	0	0	October 16
B	375	75	October 16
C	750	150	October 16
D	1000	100	October 16
E	1625	75	October 16
F	1250	0	May 2

by Andersen & Olsen (1993). Neither perennial ryegrass nor white clover undersown in oats or spring barley, pure or in mixtures, reduced the grain yield of the cereal in Papers II, III & IV. In experiments by Breland (1996), both Italian ryegrass and white clover reduced the grain yield of spring barley. The reduction was larger with Italian ryegrass than with white clover when N fertiliser was applied and about equal without N-fertiliser. Jensen (1991) and Wallgren & Lindén (1994) found no significant differences in the effect of Italian and perennial ryegrass and perennial ryegrass and red clover, respectively. However, in their experiments none of the undersown catch crops had any significant effect on grain yield.

When Italian or perennial ryegrass is undersown in relatively high yielding spring cereals, *i.e.* yielding above 4–5 Mg ha^{-1} grain dry matter, (Jensen, 1991; Wallgren & Lindén, 1994; Paper I) or if sown with a small seed rate, *i.e.* below 10 kg ha^{-1} (Kvist, 1992; Bergkvist *et al*., 1995; Aronsson, 2000; Paper II), the reduction in grain yield is, generally, too small to be observed in ordinary field experiments. In experiments with small grain yields in combination with large seed rates of ryegrass, the reduction in spring cereal yields can be substantial. Average yield losses of 3–19% have been recorded (Stokholm, 1979; Schjørring *et al*. 1988a,b; Lewan, 1994; Breland, 1996; Paper I). In agreement with Paper I, Andersen & Olsen (1993) found the largest reduction in grain yield on coarse sandy soils and the smallest on clayey soils.

The shoot dry matter of Italian ryegrass, perennial ryegrass and red clover by the time of the harvest of barley was, on average, 0.45, 0.29 and 0.27 Mg ha^{-1}, respectively, at the 80 kg ha^{-1} N rate (Paper I). The production of the ryegrasses was similar at the 40 kg ha^{-1} N rate, but the production of red clover was about doubled. In the experiments by Jensen (1991) and Andersen & Olsen (1993), Italian ryegrass accumulated more N during summer and autumn than perennial ryegrass. In Paper I, it is shown that this difference mainly occurs before the harvest of barley. The increased uptake with Italian ryegrass can, therefore, be suspected to occur at the expense of reduced N-uptake of the barley and not only improve its capacity as a catch crop. This is supported by Andersen & Olsen (1993), who found that Italian and perennial ryegrass were about as effective in depleting the soil profile on SMN late in autumn and that they had significantly different effects on grain and N yield of spring barley (Andersen & Olsen, 1993).

Cover crops, in which 20 or 40% of the perennial ryegrass seeds were replaced with equivalent amounts of white clover accumulated, on average, 5–12 kg ha^{-1} more N in the shoots during summer and autumn than the pure ryegrass on the sandy soil at Mellby (Paper II). The white clover in the mixtures established poorly on the clayey soil at Lanna (Paper II) and there was also no increase in the N accumulation with white clover in the mixture at Lanna. The positive effect on N accumulation of including white clover was most evident in the second experiment at Mellby (Mellby II), where little SMN was available. This corresponds with Lyngstad and Børresen (1996) who found that the N yield of relay cropped pure ryegrass was smaller than the N yield of the mixture with white clover at small or modest rates of N fertiliser, but was as large at high rates. The suggested larger N fixation at small supplies of N than at large should, therefore, contribute towards increasing the efficiency by which cover crops use resources at small N supplies.

Time of undersowing

The shoot dry matter of perennial crops by the harvest of spring barley became significantly smaller with each delay in the sowing of the perennial crop in relation to the sowing of barley (Paper I). The amount of perennial ryegrass by the time of harvest of barley after undersowing when the barley reached DC09, which generally coincides with the emergence of barley, was, on average, only about one third of the amount after undersowing in connection with the sowing of barley (DC00). The proportional reduction of biomass with delayed undersowing was about as large at the fertile site, Säby, as at the less fertile site, Tönnersa, but in absolute amounts the differences were much larger at Tönnersa. There was also a tendency for the perennial crops to cause a reduction in the grain yield of the cereal when undersown at DC00 or DC05 at Tönnersa, but not at Säby (Paper I). Barley undersown at DC13 tended to yield less grain than barley with earlier undersowings. This might be due to mechanical damage on barley plants caused by the drilling procedure. Plants are particularly sensitive to mechanical damage from one leaf fully developed until tillers emerge (Brouwer, 1972).

The shoot dry matter of the perennial crops by the time of harvest of barley after undersowing when the barley had three leaves was only 4–12 % of the biomass after undersowing at DC00 (Paper I). In spite of large differences in the amount of shoots of the perennial crops by the time of harvest of barley, the biomass increase during autumn was similar with undersowings at DC09 or earlier. The about 30 kg ha^{-1} shoot dry matter by the time of harvest of barley with sowing at DC 13 at Säby, was not enough to produce as large an increase in biomass during autumn as with earlier undersowings. The about 100 kg ha^{-1} produced after sowing at DC13 at Tönnersa was, however, enough. It was only when the biomass was less than about 50 kg ha^{-1} dry matter or when the cover crop stand was very dense that the net increase in shoot dry matter of the cover crops during autumn was significantly smaller than in the treatment with the largest biomass production. In the dense stands the reduction was probably due to intraspecific competition (Kvist, 1992).

Management of cover crops in practice

The most suitable dry matter production of an undersown perennial crop during the growth of the companion cereal depends on the intended use of the crop. In Papers I–IV, the intended use was mainly as a catch crop for N and/or as a green manure crop. When used as a catch or green manure crop, the growth and N uptake of the crop during late summer and autumn is the main focus. Thus, to reduce the risk of a negative effect on grain yield, its biomass at the harvest of the companion cereal should be as small as possible without risking reduced growth and N-uptake by the crop during autumn. When the perennial crops are used in leys or pastures the absolute amounts are more important and should be weighted against expected reductions in cereal grain yield with increased dry matter production and N accumulation of the perennial crop.

Due to the smaller effect on grain yield of perennial ryegrass than Italian ryegrass and the small differences found in biomass production during autumn, it can be concluded that perennial ryegrass is a more suitable catch crop than Italian ryegrass. This conclusion may, however, not always be valid. As can be seen in Table 2 and Figure 2 in Paper I, the amount of Italian ryegrass by the harvest of spring barley can be reduced to the same amount as with perennial ryegrass if the undersowing is delayed. Another way to reduce the competitive pressure from the ryegrass is to reduce its seed rate (Kvist, 1992; Bergkvist *et al*., 1995). Thus, the optimum seed rate with Italian ryegrass is smaller than with perennial ryegrass. I conclude that in fields with expected grain yields of spring cereals above 4–5 Mg ha^{-1} dry matter, the species selection should be made on the basis of the cost of seeds and sowing with the different species. In situations with very competitive main crops, perennial ryegrass may not be competitive enough to establish safely. Perennial ryegrass undersown in the spring in winter wheat, which is generally more competitive than spring cereals, established poorly in some of the experiments presented by von Schultheiss & von Boberfeld (1994), Ohlander *et al*. (1996) and Hjellström (2001). In experiments by Bergkvist *et al*. (2002), perennial ryegrass established well in winter wheat, but its biomass increase during autumn was only two thirds of the biomass increase with Italian ryegrass at the most fertile site. The difference was smaller on the less fertile site where competition for light was less severe. Perennial ryegrass is probably a better choice than Italian ryegrass in most situations when the expected grain yields are below 4 Mg ha^{-1}.

I see two main reasons to be cautious when choosing Italian instead of perennial ryegrass as a catch crop for nitrogen. Italian ryegrass has the potential to produce larger yield losses than perennial ryegrass and Italian ryegrass is more prone to produce seeds during the year of establishment than perennial ryegrass. Those seeds may increase the risk of the grass species appearing as a weed later in the crop sequence.

It is more important with red and white clover than with the ryegrasses that there is moisture available at sowing. It seems, therefore, better to affect the amount of clover by regulating the seed rate than by delaying the sowing, especially if the risk of dry weather during spring is large. The availability of nitrogen has a much larger effect on the biomasses of the clovers than a short delay in undersowing (Paper I). Thus a smaller seed rate can be used with poor availability of N than with good.

Another way to manipulate the amount of both clovers and grasses is to adjust the seed rate of the main crop (Kvist, 1992). That is, however, likely to affect the economy of the main crop and can therefore only be considered when the understorey crop is of great economic importance, *i.e.* establishment of rotational leys. The method of establishment is also of importance when establishing understorey crops (Bergkvist *et al*., 1995; Känkänen *et al*., 2001). With a safe method of establishment a smaller seed rate can be used (Bergkvist *et al*., 1995).

Soil mineral nitrogen

The content of nitrate in the topsoil was smaller already by the time of oat harvest in treatments with perennial ryegrass in the cover crop at Mellby 2, but not at the other sites (Paper II). There was much precipitation during the summer when Mellby 2 was established and precipitation during summer generally correlates with good growth of undersown perennial crops (Schröder *et al*., 1997). The cover crop dry matter was about 0.40 Mg ha^{-1} at Mellby 2 and about 0.10 Mg ha^{-1} after the dry summer when Mellby 1 was established. The amount of SMN late in autumn in treatments that included perennial ryegrass was 25, 13 and 4 kg ha^{-1} smaller than in those without a cover crop at Mellby 1, Mellby 2 and Lanna, respectively. However, about half of the N in the cover crops could not be accounted for in the treatments without a cover crop, either as SMN or in weeds (Paper II). In an experiment adjacent to the experiments at Mellby, Aronsson & Torstensson (1998) observed large leaching from August to November. Something similar probably also happened in the experiments at Mellby (Paper II). This compromises the assumption that the growth of the cover crops up to the harvest of the spring cereal should be as small as possible without negatively affecting autumn growth. With early growth of the cover crops, much of the leaching may have been prevented and such early growth may affect grain yield negatively. The soil texture at Mellby, where the differences were greatest, causes poor root growth in the subsoil and poor water holding capacity. In such conditions, cover crops may prevent nitrate from entering the subsoil rather than emptying the subsoil. This suggests that the leaching may be smaller with cover crops that are dense than with those that are sparse by the time of harvest of spring cereals, even if the increase in biomass during autumn is similar. However, soils generally contain little SMN after harvest of a cereal crop (Wallgren and Lindén, 1994; Schröder *et al*., 1996) and most soils allow more root growth in the subsoil than the soils at Mellby. This suggests that the assumption that the growth up to the harvest of the spring cereal should be as small as possible without negatively affecting autumn growth will frequently be adequate.

White clover undersown in spring cereals was not able to reduce the content of SMN late in autumn compared to the control treatments with weeds and volunteer cereals (Papers II, IV). This corresponds well to what was found by Lyngstad & Børresen (1996) and with red clover by Wallgren & Lindén (1994). The mixtures were, however, about as effective as pure ryegrass (Paper II). The effect of the cover crops on SMN before sowing in spring interacted with time of incorporation

(Paper II). The SMN after pure ryegrass was smaller than in the control after incorporation in the spring, but after autumn ploughing the amounts was rather similar. The grass–clover mixture kept the SMN as low before sowing in spring as the pure ryegrass when the cover crops were incorporated in the spring, but when they were ploughed under in the autumn the level of SMN was higher and more resembled the content of the treatment with incorporated pure white clover. White clover incorporated in the spring tended to increase SMN compared to the control (Paper II). The content of SMN in winter wheat growing with understorey white clover was larger than in pure wheat (Paper IV). Thus it is likely that pure white clover or crops dominated by white clover will have more SMN in the spring than if weeds or sparse winter cereal crops are allowed to grow undisturbed during autumn and winter.

Effect on subsequent crop

Pure perennial ryegrass had no notable effect on the grain yield of the subsequent crop when ploughed under in the autumn. (Paper II). After spring ploughing the effect tended to be negative at Mellby 1 and was clearly negative at Lanna. The N uptake tended, however, to be larger after ryegrass than after fallow, regardless of time of incorporation at Mellby. The N may have become available too late to increase yields. Both positive and negative effects of incorporated ryegrass cover crops on the grain yield of the subsequent crop have been reported in the literature. Thorup-Kristensen (1993) explains the varying effect of cover crops on grain yield with the effect of pre-emptive competition. Only a fraction of the N taken up by cover crops becomes available to the subsequent crop. That fraction varies with species and is larger for clover than for grass. From the fraction that is released should be subtracted the amount of SMN that would not have been lost if there were no cover crop. The fraction of N withheld is larger on clayey soils than on sandy, because leaching is smaller and rooting depth larger. The fraction withheld also depends on when it is taken up. SMN available early in the autumn is likely to be lost from the soil during winter if not taken up by a cover crop, while SMN available in the spring is unlikely to be lost. Therefore, according to Thorup-Kristensen & Nielsen (1998), cover crops should not be allowed to reassume growth in spring. To avoid this, they suggest that the cover crops should either be incorporated before reassuming growth in spring or that non-winter hardy species be used. Suitable species according to Thorup-Kristensen & Nielsen (1998) are for instance phacelia (*Phacelia tanacetifolia* Benth.) and oil radish (*Rhaphanus sativus* var. *niger* L.). Those species establish quickly and their roots can reach great depths in a short time period (Thorup-Kristensen, 2001). The establishment of those species after cereals is, however, risky under conditions with short growing seasons, as in the Nordic countries. If they are undersown in spring or early summer they will flower and stop growing before autumn. If annual crops are sown later than in the beginning of August their biomass and N uptake during autumn will in many years be insignificant (Rasmusen & Andersen, 1991; Catt *et al*., 1992). The present results show that the subsequent crop benefits more from the cover crop as the proportion of the clover increases (Paper II). The effect was more due to changes in the quality of the residues than on increased N accumulation with clover in the mixture. White clover biomass decreases more during winter than that of grasses (Wachendorf *et al*., 2001) and white clover releases much of its nitrogen during late autumn and winter (Goodman, 1991). The negative effect on N use efficiency of using winter hardy grass species as catch crops for nitrogen can, therefore, be reduced or eliminated by including white clover in the catch crop (Paper II). Varieties of white clover differing in winter hardiness had different effects on the grain yield of intercropped wheat (Paper III). This suggests that varieties adapted to a warmer climate than that on the site of growth will produce the largest residual N-effect, because the N will be released earlier than with more adapted varieties.

White clover – winter annual intercropping

Grain yield of the first crop of wheat or oilseed rape

The grain yield of winter wheat direct drilled into a living crop of white clover was, on average, 3.4 and 1.0 Mg ha^{-1} less than wheat alone in the first crop of wheat at Lönnstorp and Lanna, respectively (Paper IV). Clements (1998) reports, on average, 3 Mg ha^{-1} smaller grain yields of winter wheat intercropped with white clover than of conventionally grown wheat, when the intercropping system was fertilised with 50 kg N ha^{-1} and the conventional system with about 200 kg N ha^{-1}. In a previous unpublished experiment, there was no harvestable winter rape after direct drilling of rape into white clover that had been undersown in spring barley the same year (results not shown). Stenberg *et al*. (1998) measured 60–70% smaller yield when winter rape was direct drilled into a white clover crop than when it was direct drilled into barley stubble. Thus, the results from the first year correlated well with other findings and were not promising.

Measures taken to reduce competition from the clover and improve the availability of N to the wheat were not successful enough (Paper IV). The reduction of clover biomass after applying the herbicide tribenuronmethyl about two weeks before the predicted start of stem elongation of wheat increased the grain yield of wheat in the intercrops by, on average, 1.4 and 0.4 Mg ha^{-1} at Lönnstorp and Lanna, respectively. That means that only about half of the reduction in grain yield with a white clover understorey was avoided. Mowing at the emergence of wheat and spring harrowing was not an effective means of increasing grain yields (Paper IV). The white clover recovered quickly after the mowing and the spring harrowing probably caused damage both to wheat and white clover. Several studies have shown that the competitive effect of white clover in intercropping systems with cereals can be reduced by causing selective damage to the clover with physical (Grubinger & Minotti, 1990; Thorsted *et al*., 2002) or chemical (Williams & Hayes, 1991; Jones, 1992) means. In the system described by Clements & Donaldson (1997) and Clements (1998), paraquat was applied before sowing of wheat to control weeds, but also to restrict clover growth. The methods described in the references above do, however, require special equipment, special row arrangements, use of herbicides when the weeds are in poor growth and/or the use of environmentally unfriendly herbicides. Therefore, none of the methods were considered a good option in the present study.

In two experiments carried out at Lönnstorp, there were large differences in the economic yield of winter wheat or winter oilseed rape after direct drilling into different varieties of white clover (Paper III). The clover variety "Sonja", which was used in the experiments presented in Paper IV, in the unpublished experiment with rape and in Stenberg *et al*. (1998), reduced the grain yield of wheat by almost 2 Mg ha^{-1}, while AberCrest had a negligible effect on grain yield. The seed yield of rape was reduced to nothing with Sonja, but when the rape was sown at high density with AberCrest, seed yields were about equal with and without understorey white clover (Paper III). The economic yields with the clover variety S184 were intermediate in both experiments. AberCrest was the least winter hardy of the tested varieties. It had as large biomass late in autumn as the other varieties, but lost more biomass during winter and started to grow later in spring than the more winter hardy varieties (Paper III). The small leafed "S184" had about the same growth pattern as "Sonja", but produced less biomass. Neither Clements (1998) nor Thorsted *et al*. (2002) reported large differences among clover varieties on their effect on the grain yield of winter wheat and oats, respectively, when the white clover was used as a perennial understorey crop. However, they did not test the hypothesis that a less winter hardy variety would be more suitable than varieties better adapted to the local climate.

Grain yield of the second crop of wheat

The individual shoot weight of wheat late in autumn in the first wheat crop at Lönnstorp was 68 and 28 mg in the sole cropped and intercropped wheat, respectively. At Lanna, the wheat plants in the sole cropped systems were, on average, 30% heavier than in the intercrops. The white clover crop appeared even denser after the first crop of wheat than after the spring barley one year earlier (Papers III, IV). Therefore, I considered it necessary to make some change in the management of the second crop of wheat. The change consisted of a tillage operation carried out within one week before sowing of wheat (Papers III, IV, Complement I, II). With this change in management, the intercrops contained about equal quantities of wheat and white clover in late autumn. The mean individual shoot weight of wheat was 32 and 54 mg in the sole cropped and intercropped wheat, respectively, at Lönnstorp and did not differ significantly between systems at Lanna (Paper IV). The second crop of wheat yielded 1.3 and 1.2 Mg ha^{-1} more respectively with clover at Lönnstorp and Lanna, in the experiments presented in Paper IV, and 0.4 Mg ha^{-1} more in the experiment presented in Paper III. The wheat plants were larger after Sonja than after S184 and AberCrest, suggesting differences in residual effect. There were, however, no differences in the effect of white clover variety on the grain yield of the second crop of wheat (Paper III). In spite of the dramatic effect of the herbicide on the clover in the first crop of wheat in the experiments presented in Paper IV, the intercrop dry weight and proportion of clover in the autumn and content of SMN and the grain yield of the second crop of wheat were similar to those without the herbicide treatment. Thus, it seems as though enough residual N effect can be achieved with moderate amounts of clover. The tillage operation performed before sowing of wheat might, therefore, not decrease the residual N effect experienced by a subsequent crop of wheat. The main disadvantages with tillage before sowing in

Table 3. *Effect of soil tillage before sowing of winter wheat in a crop of white clover at Logården on mean (n=4) plant density in autumn and in spring, ear density in August, amount of wheat and white clover in August and final grain yield of winter wheat*

Tillage	Plants m^{-2} Autumn	Plants m^{-2} Spring	Ears m^{-2}	Winter wheat ($Mg\ ha^{-1}$)	White clover ($Mg\ ha^{-1}$)	Grain yield ($Mg\ ha^{-1}$)
none	575	530	493	8.7	1.7	n.h. [3]
ST[1]	398	360	506	10.5	1.1	4.8
GF[2]	423	383	426	10.2	0.9	4.4
p-value	0.001	0.002	0.055	0.11	0.14	0.47
$LSD_{0.05}$	67	66	n.s.	n.s.	n.s.	n.s.

[1] cultivator with spring tines
[2] cultivator with goose foot tines
[3] not harvested, because the wheat was lodged and covered with vigorously growing white clover

autumn are that tillage increases weed emergence (Jensen, 1995) and that the increase it causes in mineralisation of N (Stokes *et al*., 1992) may increase leaching losses (Francis *et al*., 1992) and denitrification (Aulakh *et al*., 1991).

The effect of stubble cultivation before sowing of wheat

Complement I was carried out to study the effect of stubble cultivation before sowing of winter wheat. The soil was wet when the tillage and the sowing were carried out and the soil structure was, therefore, negatively affected by the tillage. Thus, more wheat plants were established after direct drilling than when sowing after stubble cultivation (Table 3). However, the white clover plants grew vigorously in the treatments with direct drilled wheat and competed strongly with the wheat. The ear numbers were similar in all treatments in August and the wheat biomass tended to be larger, suggesting larger ears, in the treatments with stubble cultivation before sowing than with direct-drilled wheat. Later in the summer, the direct drilled wheat lodged and was not possible to harvest, because of the vigorously growing clover. The wheat sown after stubble cultivation did not lodge and yielded well (Table 3). The clover understorey was also dense in the treatments with stubble cultivation, but remained well below the top of the wheat canopy.

The performance of the winter wheat–white clover intercropping system

The larger grain yields of wheat in the intercrops than in wheat alone in the second consecutive crops of wheat did not fully compensate for the small yields in the first crops. The total grain yield in the wheat intercrop was, on average, 26% smaller than with wheat alone at Lönnstorp and about equal at Lanna (Paper IV). With herbicide treated white clover, the grain yield was 8% smaller and 9% larger than with wheat alone at Lönnstorp and Lanna, respectively (Paper IV). The grain yield increased linearly with increased N rate in both crops and at both sites (Paper IV). The rate of increase was smaller with clover than without at Lönnstorp and in the second crop at Lanna. The total grain yield of three crops of winter wheat was 6% larger and 17% smaller with AberCrest and Sonja, respectively, than with wheat alone (Paper III). The results presented in Papers III and IV do not provide evidence that the white clover increases grain yield when intercropped with wheat, even at the same fertiliser levels. The N concentration in the wheat grains was, however, 4–34% higher with white clover as an understorey crop than without (Paper IV).

The N concentration in the cereal grains was also higher when the cereal was intercropped with white clover than in the cereals alone in Clements (1998) and Thorsted *et al*. (2002). There were particularly large differences in N concentration in the grains at high N rates (Figure 2 in Paper IV). The yield of N in the grain, therefore, increased linearly with increased N rate at about the same rate in all systems in the second crop of wheat at Lanna (Figure 3 in Paper IV). That means that there were no differences in the efficiency of the use of N fertiliser, in terms of N yield in the grain, between the intercropping and sole cropping systems in either of the two crops at Lanna (Paper IV). The amount of inorganic N in the soil profile was generally larger when intercropping than in wheat alone in both wheat crops at Lönnstorp. The wheat in the intercropping system was not able to deplete the soil on SMN as well as the wheat alone. This suggests that factors other than N kept grain yields smaller in the intercropped system than in wheat alone and that, therefore, the potential of the system was not fully realised in the experiments presented in Papers III and IV.

It was the number of ears m^{-2} and not the number of kernels ear^{-1} or kernel weight that was smaller in the intercropped system in the first crop of wheat at Lanna (Paper IV). Wheat plants were fewer and smaller in autumn in the intercropping system and tillering was restricted. It is not likely that the water supplies limited growth during autumn and winter. The wheat was well supplied with P and K in the experiments. It seems, therefore, likely that it was competition for light that limited the growth of wheat at the early stages. In crowded stands, few tillers per plant emerge (Gooding *et al*., 2002). The fewer plants in autumn might not only be the effect of competition, but could also be due to less favourable placement of the seeds, because the seed drill used is not completely suitable for direct drilling when the soil surface is dry and hard and with abundant crop residues, as in these experiments.

The weed control

There were few weeds in the first crop of wheat in all the experiments presented in Papers III and IV, but the second and third crops of wheat at Lönnstorp became heavily infested. The average amount of weed dry matter at flowering of the second crop of wheat in the two experiments was about 0.4 Mg ha^{-1}. Dominating species were *Apera spica-venti* (L.) P.B., *Lolium perenne* L., *Papaver rhoeas* L. and *Elymus repens* (L.) Gould. Species that are rare in ploughed systems, such as *Bromus hordeaceus* L. and *Bromus sterilis* L., were also frequent in patches. It is likely that the large weed biomasses in the second and third crops at Lönnstorp interfered with the potential to produce large grain yields. The introduction of the

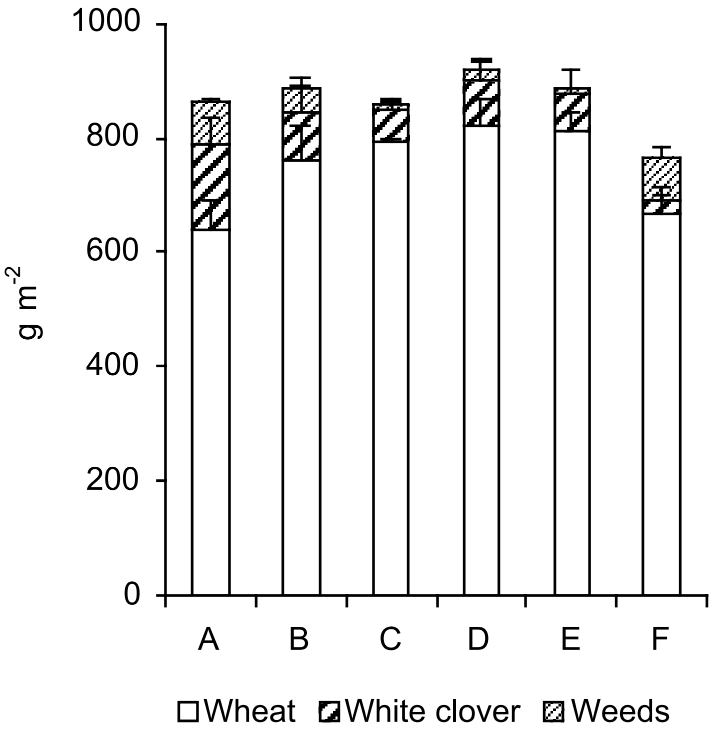

Figure 1. *The effect of autumn or spring application of isoproturon and diflufenican on mean (n=3) amount of winter wheat, white clover and weeds at flowering of a third consecutive crop of winter wheat sown in white clover living mulch at Lönnstorp. Bars are standard errors (treatments, see Table 2).*

stubble cultivation before sowing seems to have solved the problem with too competitive clover, without severely reducing the positive residual effect of the clover on the subsequent crop. The abundant occurrence of weeds seemed, therefore, to be the major limitation of the system. Grass weeds also propagated rapidly in the experiments reported by Clements & Donaldson (1997), but they solved the problem by spraying paraquat before sowing wheat. The problematic weeds had few or no leaves at that time in the present experiments or were only present as seeds. Paraquat is forbidden in Sweden, due to environmental reasons. Alternative herbicides are expensive and probably not very efficient because of the reasons mentioned above.

Herbicides containing diflufenican and isoproturon are commonly used in winter wheat production in southern Sweden and are considered efficient against the annual weeds dominating in the experiment. Since the herbicides mainly act as germination inhibitors and the white clover was well established, it was hypothesized that the herbicides would efficiently control weeds, but only temporarily check clover growth (Complement 2). The results showed that the application of isoproturon and diflufenican in the autumn reduced the amount of annual weeds to 1–13% of the amount in the control treatment (Table 4; Figure 1). No effect was found on perennial weeds. The amount of white clover at flowering

Table 4. *The effect of herbicide treatment on the mean (n=3) amount of annual and perennial weeds at flowering of a third consecutive crop of winter wheat sown in white clover living mulch at Lönnstorp, grain yield of wheat, yield of N in grains and white clover ground cover in early September, in time for a fourth crop of wheat to be sown (treatments, see Table 2)*

Herbicide treatment	Annual weeds (g m^{-2})	Perennial weeds (g m^{-2})	Grain yield (Mg ha^{-1})	N yield (kg ha^{-1})	White clover (%)
A	55.9	19.1	4.0	45	74
B	6.8	35.3	5.2	59	84
C	0.5	8.6	6.1	70	81
D	7.3	11.1	5.8	70	86
E	0.7	7.9	6.1	71	75
F	51.3	25.1	4.6	58	30
p-value	<0.001	0.19	0.003	0.006	0.086
$LSD_{0.05}$	23.1	n.s.	0.84	12.5	n.s.

of wheat was reduced by the herbicides (Figure 1), but the ground cover of white clover by the time of sowing a fourth consecutive crop of winter wheat was satisfactory, even at the highest doses of the herbicides (Table 4). The wheat yielded, on average, 1.8 Mg ha^{-1} more grains after herbicide treatment in the autumn than in the control (Table 4). The spring application of isoproturon neither affected the amount of annual weeds nor the grain yield, but reduced the amount of clover more than the autumn treatments. That treatment resembles the treatment with tribenuronmethyl in Paper IV. The present results suggest that the autumn application of diflufenican and isoprutoron is better suited to the system than applications of herbicides in the spring. The present experiment was heavily infested with weeds. When the weed pressure is less severe, it might be possible to use a smaller dose than that indicated by the results of Complement 2. That would decrease the cost of the herbicide and reduce the risk of the clover not surviving the damage caused by the herbicides.

Concluding remarks

Undersown perennial ryegrass is the most commonly used cover crop grown with the purpose to reduce the leaching of N from arable land to surface and ground waters in Sweden. The results presented in the present thesis indicate that Italian ryegrass in some situations would be just as suitable or even more suitable. The better growth of Italian than perennial ryegrass is an advantage as long as the seed rate can be reduced or undersowing delayed further with maintained good soil cover in the autumn and without risking damage to the main crop with late undersowings. Italian ryegrass, generally, suits best with competitive main crops, delayed undersowing and probably also with late sowing of the main crop. Perennial ryegrass has the advantage of being safer to use. The risk that it reduces grain yield is smaller than with Italian ryegrass and if it is established properly there is much evidence showing that it reduces N leaching effectively. Therefore, I see no reason to change the present general recommendation of using perennial ryegrass as a catch crop, when the undersowing is carried out in spring cereals. Italian ryegrass should be considered as an option for competitively harsh situations.

Ryegrass cover crops generally reduce N-losses, but do not increase the N-uptake of the subsequent crop substantially. They should, therefore, add to the N-content of the soil. This implies a long-term increase in mineralisation of N from the soil and thus a risk of increased leaching losses in the future. The results presented in Paper II indicate that with the inclusion of white clover in the cover crop, more N will become available to the subsequent crop. The N fertiliser requirements may, therefore, be reduced and/or the harvested N yield of the subsequent crop increased more than is fixed by the clover. This suggests that the inclusion of clover in the cover crop may improve its long-term effect as an N catch crop. Red clover fits better than white clover with most herbicides in common use and is more competitive. Red clover, therefore, suits better than white clover when using herbicides and in high yielding crops. The mineralisation of N is, however, slower from red than from white clover (Marstorp & Kirchmann, 1991). White clover is, therefore, probably better suited than red clover for spring ploughing.

Large grain yields of wheat can be produced in a winter wheat – white clover intercropping system. However, the competition from the clover needs to be kept low during tillering of wheat. To achieve that in relatively low input systems, the results in this thesis point to two main options. One option is to use a white clover variety that is not as winter hardy as the varieties most suitable in forage leys in the same area. With this strategy it might only be necessary to conduct small measures to reduce competition from the clover during autumn. The tillage carried out by the sowing equipment or the application of a suitable herbicide when the wheat has 1–2 leaves might be enough. The second option is to carry out a separate tillage operation before sowing of wheat. With this strategy it is possible to use well-adapted varieties of white clover. The risk of achieving a very competitive stand of clover is small and, therefore, the risk of large yield losses due to the clover is probably also small. The tillage will, however, increase the amount of N that will be mineralised during autumn and much of the N that is released during the rapid initial mineralisation of N might be lost from the system. The tillage might also stimulate germination of weeds and reduce the competitive effect of white clover on weeds. This might increase the need for purchased inputs like N fertilisers and herbicides.

I conclude that, (1) the tillage carried out in connection with the sowing of wheat, (2) the weed control practice, and (3) the choice of clover variety, are three parameters that have large effect on the grain yield of winter wheat in the intercropping system. The effect of these three parameters and their interactions needs further attention in order to get the information required to give clear recommendations. I think that to develop locally adapted guidelines the further development of the system would benefit from an active cooperation between researches, supervisors and farmers.

I believe there is a need for publicly funded research in agronomy to focus on the use of the work of Nature in arable cropping systems. Private companies cannot be expected to support this kind of research financially, because a successful development in this field means that the market for inputs diminishes. Much can, however, be gained by farmers and consumers if expensive inputs can be replaced by the free work of Nature. I also believe that future research should aim at introducing more functional diversity into the landscape and to find how this diversity can be used to alleviate the need for inputs from outside the system. It is important to keep in mind that this work must both aim at preparing for future situations with *e.g.* less high quality fossil fuel supporting the economic system and present solutions adapted to the surrounding economy. It is my hope that this kind of research will bring researchers in agronomy and ecology closer together.

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Acknowledgements

I would like to thank all of you who have contributed to this thesis or to my wellbeing while preparing it.

Special thanks to:
Lars Ohlander, who managed to be my main supervisor, good friend and mentor in one and the same person. Bodil Frankow-Lindberg for your good help and for telling me things like “that will take you about 33 minutes per sample”. Tomas Rydberg for encouragement and good advice.

Anders, Eskil, och Erik på Lönnstorp. Rolf och Johan på Lanna. Erik och Lars med medarbetare på L:a Böslid och Munkagårdsskolan. Johan och Nisse på Logården. Jan, Henrik, Sven-Erik och Mulle på Ultuna. Gun-Marie, Sonja, Miklos med flera på provcentralen. Ni har varit ovärderliga i fältarbetet. Birgitta, Gudrun, Gunilla, K-G, Per och Stina för god administration och smörjning av datorn.

Gunnar Ekbohm for your good advice and the interesting discussions. Mary McAfee and Nigel Rollison for improving my English. Börje Lindén and Johanna Björklund for comments on different manuscripts.

Bob Clements for good co-operation.

Helena Aronsson, Maria Stenberg, Nilla Nilsdotter-Linde, Mats Kvist, Fredrik Stendahl, Mats Höglind and Torsten Andersson for being my appreciated co-workers in different projects. Sten Ebbersten, Carl-Anders Helander, Anders Olsson and Henrik Stadig for your help and friendship.

Bengt Andersson and Hans-Arne Jönsson at SW for supplying seeds and for useful information.

Fellow PhD-students at the former Department of Crop Production Science and the present Department of Ecology and Crop Production Science. All members of the faculty research team “Terejot”.

Morfar för att du gav mig intresse för hur man brukar jorden och för att du, med osvikligt tålamod, svarade på miljoner frågor när jag var liten. Mina föräldrar och min bror.

Karin, Erik, David, Maria och Oskar. Inte för att ni precis hjälpt till med avhandlingen, men för att ni finns, stöttar mig och får mig att tänka på viktigare saker än bottengrödor.

Financial support was provided by the Swedish Council for Forestry and Agricultural Research, the Swedish Farmers’ Foundation for Agricultural Research, the Swedish Board of Agriculture and the Swedish University of Agricultural Sciences.