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The potential for leguminous crops in Scotland

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1 Executive summary

1.1 Aims

The Scottish Government is committed to reducing greenhouse gas (GHG) emissions from agriculture as part of its pledge to achieve net-zero emissions in Scotland by 2045. In 2018, agriculture accounted for 18% of Scotland's total GHG emissions, with a significant share coming from nitrogen fertilisers (1.4% of Scotland's total GHG emissions are from soil as a consequence of applying nitrogen fertilisers). Scotland's Climate Change Plan update[1] envisages that nitrogen emissions, including from nitrogen fertiliser, will have fallen through a combination of improved understanding, efficiencies and improved soil condition (SG 2020c, 238).

One policy approach identified as having potential to deliver this outcome is through the use of leguminous crops to fix atmospheric nitrogen, potentially reducing the need for synthetic fertiliser. Increasing legume production could also help build protein self-sufficiency in Scotland.

This study assesses the opportunities, challenges and barriers influencing potential production of grain and forage legumes in Scotland. Grain legumes are crops such as beans and peas which are cultivated for their seeds and used for both human and animal consumption. Forage legumes include lucerne (also known as alfalfa), clover and vetch which are sown in pasture and grazed by livestock or used for cutting for hay or silage.

We assess the climate mitigation potential of legumes within arable and grassland rotations and comment on the potential to reduce reliance on imported protein.

1.2 Key findings

Current production and trends

- There has been a historical decline in the grain legume area in the EU, largely as a result of economic forces. This is matched in Scotland. The market output of

[1] https://www.gov.scot/publications/securing-green-recovery-path-net-zero-update-climate-change-plan-20182032/

legumes has been relatively low and volatile compared to other crops, and there currently is a low level of production (2.3% of the tillage crop area in Scotland).

- Use of legumes within forage grazing is an accepted practice in Scotland and large areas of improved grassland benefit from their inclusion. There is little scope for an expansion in the area of legumes in pasture.

Availability of land

- There is a large area of land which is **theoretically** suitable for legume crops growth. Generally, the most suitable land lies in the east of Scotland and the lowlands. However, Scotland's climate can pose issues for cultivation (e.g. grain legume establishment and harvest), leading to a perception among some farmers of poor crop performance.
- Climate change is not expected to have a major effect on the area of land that can support legume crops in Scotland. Under the Met Office (UKCP18[2]) climate predictions for Scotland, the area of **theoretically** suitable land for forage and grain legume crops will decrease slightly in 2040-2059 and increase thereafter.

Greenhouse gas emissions

- The main way to reduce GHG emissions is through crop substitution, increasing the use of leguminous crops. This results in:
  - changes in nitrous oxide emission from soil (through changes in nitrogen fertiliser use and crop residue returns to the soil); and
  - lower emissions from manufacture of nitrogen fertiliser (occurring outwith Scotland).
- Including legumes in crop rotation, one year in five, could lead to an annualised nitrogen saving of 30.8 kg/ha. This is a saving of 24.1%, and 16.1 kt for Scotland.
- The savings in GHG emissions from including legumes are 107.4 kt CO_2e/yr, rising to 160.8 kt CO_2e/yr when fertiliser manufacture GHG emissions (outwith Scotland) are included. This is equivalent to 1.4% of Scotland's agriculture emissions, rising to 2.2% when fertiliser manufacture GHG emissions are included.

Market and other constraints and opportunities

- The UK is reliant on imports to provide 47% of protein sources used in animal feeds. With greater political and public awareness of the need for sustainable protein, the importance of domestic protein sources is set to increase.
- Economic conditions for both demand and supply are key influences on the area of legumes grown. As an ingredient in animal feed, legumes can be uncompetitive with other protein sources. Soya is cheaper and provides a better nutritional balance for some species (such as pigs and poultry) which makes it both economically and technically more attractive. In the case of ruminant feeds, there are cheaper sources of protein available (such as distillery by-products, oilseed rape meal and sunflower meal).
- From a grower's perspective, the price paid for legumes is too low and other cropping options give higher and more reliable returns. There are also risks in reliability of production (weather related failures, and yield variability). However, new

[2] https://www.metoffice.gov.uk/research/approach/collaboration/ukcp/about

markets for human food ingredients and a growing demand in the fish feed sector could offer opportunities for Scottish growers.
- There are a range of technical and logistical limitations which depress the market for grain legumes. These may require some intervention but should not be significant, long-term barriers to increases in legume production. A lack of production has limited investment in the necessary infrastructure in Scotland – there are no mills equipped to process peas and beans (dehulling, fractionation) which is required to provide products direct to feed companies in Scotland. This lack of infrastructure limits the willingness to grow grain legumes and also the willingness of grain traders to purchase and trade them.
- Perceived poor performance of grain legumes in Scotland has suppressed the area cropped. However, greater awareness amongst the industry of the potential of legumes to support more sustainable rotations and support soil health, and to help manage disease and "regenerate" land, are increasing interest in legumes (both grain and forage species).

Our main findings on the strengths, weaknesses, opportunities and threats are captured in the table below:

Strengths, Weaknesses, Opportunities and Threats for Legumes production in Scotland

Strengths	Weaknesses
• Environmental benefits for GHG, soil, water and biodiversity are well established. • Can support more diverse rotations – reducing costs and artificial nitrogen fertiliser inputs. • Scottish condition offers some advantage for food grade bean production (low pest pressure). • Forage legumes accepted and widely used. • Can support improved efficiency in livestock production through improved forage and grazing quality. • Reduces the need for artificial fertilisers thereby reducing greenhouse gas emissions. • Reduced chemical input can benefit biodiversity. • Fresh Pea production – specialised and well established with significant infrastructure already in place.	• Growing conditions can be challenging for both establishment and harvest (wet weather, late maturing). • Perhaps most significantly, market demand for grain legumes is low due to competition from other alternative and cheaper sources. • Confidence in production is low. • Susceptible to weather variations – can result in variable yields. • Poorer economic performance compared to other crops e.g. cereals and oilseed rape. • Soil pH can be an issue in Scotland.

Opportunities	Threats
• New markets and increased awareness of the benefits of legumes. Pea protein consumption doubled globally between 2015 and 2020 with the rise in plant-based meat alternatives. • Significant increases in human consumption market projected. • Decreased fertiliser use across a rotation. • Cost savings through reduced fertiliser use. • Decreased GHG emissions across a rotation. • Global pressure on other protein sources could increase demand (improve price and financial viability). • Improved self-sufficiency in domestic protein sources (both forage and grain). • Human consumption with premium price could support increase production. • New production systems (e.g. intercropping, new species and varieties). • Improved soil fertility. • Soil Health benefits driving interest and more holistic perspective, this is supporting reinvigorated interest in legumes.	• Loss of production technologies (varieties, plant protection products, advice and agronomy support). • Cultural resistance to growing grain legumes (farmers have had poor experiences; whole sector is risk averse so will not try to grow them). • Poor economic performance – Brexit impacts could exacerbate these in particular the premium human consumption market. • Disease spread – bruchid beetle, chocolate spot, foot rot and damping off. Rhizoctonia in the soil is a major factor, seed treatments no longer available. • Vining pea (fresh peas/beans) require land to be free of any pea or bean crop for 6 years prior to establishment. These areas of land are already well established around the processing plants. Increases in combinable peas and beans in these areas could significantly impact upon this production.

Contents

2 The context for legumes in Scotland

The inclusion of legumes into arable and forage production systems has been widely studied and the environmental, economic and agronomic opportunities well documented (Preissel et al., 2014; Watson et al., 2017). Globally, legumes are the second most important family of agricultural crops (after grass) accounting for 14.5% of the arable area globally (Watson et al, 2017). Across Europe, the area of grain legumes has fallen from a high of 5.8 million hectares (M ha) in 1961 (FAO, 2020) to just 2.36 M ha, making up only 2.2% of the arable area of the European Union. This is a pattern that is repeated in Scotland, with the area of field beans and peas representing just 0.4% of the tillage area in 2020 (2,466 ha) (Scottish Government, 2020b). The market for vining peas is much stronger than the grain legumes market, with approximately 9,000 ha (about 1.7% of the tillage area) grown by specialist producers in 2020.

In recent years, there has been an increase in the demand for high quality protein. This has been driven by a number of factors, including: changes in livestock production techniques, changing regulations on protein sources for livestock production and growing levels of disposable income with consequent increased demand for meat and dairy products (Billen et al., 2012; Lassaletta et al., 2014). This is particularly relevant to Scotland due to the importance of beef, dairy and fish production to the economy. These sectors all have a high demand for vegetable protein and in line with other livestock systems in Europe, rely on significant imports of protein crops from across the world — especially soya beans and soy meal as well as sunflower and rape seed-based sources. Scotland relies on imported sources of protein with 47% of proteins in livestock feed sourced from outside the UK (Stakeholder Communications, 2020). Concerns over the sustainability of these protein sources are growing: supply chains, including supermarkets, farmers, feed suppliers and the general public at large are becoming increasingly aware of the environmental pressures that these sources of protein can have on the global environment such as deforestation, land degradation and climate impacts (Zander et al., 2016; Clark, 2020 and WWF, 2017; Stakeholder communication, 2020).

The domestic production of crops (and in particular legume crops) can support reduced reliance on imported protein sources (grain proteins like faba beans, combining peas, oilseed rape). While the area of grain legumes accounts for a relatively small area, the wider production/use of leguminous crops in Scotland needs to consider forage legumes. The use of clover within improved and reseeded grassland is widely adopted, with over 95% of all reseeded grassland including either white or red clover mixes (Stakeholder communication, 2020). The use of legumes within forage have been shown to provide environmental and economic benefits to livestock production. While it is difficult to quantify the exact area of land benefitting from legumes, their use is an accepted practice in Scotland and large areas of improved grassland would benefit from their inclusion.

Legumes can provide wider environmental and agronomic benefits (Legume Futures, 2014; Watson et al., 2017). In particular, the role that legumes can provide in reducing the greenhouse gas emissions (GHG) from agriculture in Scotland is of specific relevance to this study (Scottish Government, 2018). In additon to the focus on GHGs, there is growing interest in the role legumes can play in future dietary change in response to climate and also their role in health and the nutritional quality of food (Lancet, 2019; Foyer et al., 2016).

This study provides an assessment of the opportunities, challenges and barriers influencing potential production of legumes. We assess the climate mitigation potential of legumes within arable and grassland rotations and comment on the potential to reduce reliance on imported protein.

3 Critical demand and supply factors

3.1 Demand – uses of legumes/protein

Demand for legumes can be differentiated into two major groups:

- grain legumes (e.g. peas, beans, soybeans including fresh peas and beans) used either directly or as processed grains for livestock (including fish) and human consumption.
- forage legumes (clovers, vetches) used either for direct grazing, cutting for hay or ensilaging to provide saved feed. They may also be used as part of cover crops or non-grazed leys to protect soils or provide “green manure” (plant derived nitrogen through nitrogen fixation) released for following crops.

3.1.1 Grain legumes

The demand for legumes is complex with many uses, markets and sources of protein available globally. At a very simplistic level, however, there are two primary demands for protein sources within Scotland: proteins for human consumption (e.g. fresh peas, lentils) and those used in the production of animal feeds.

The production of compound feeds for livestock utilises a range of raw materials. Those listed below provide elements of the protein requirements of the finished feed and are blended to achieve the specific nutritional balance desired. The main ingredients utilised within animal feeds in the UK are (AHDB, 2020):

- wheat
- oats
- barley
- confectionary by-products
- cereal by-products
- distillery by-products
- whole oilseeds
- protein concentrates
- maize
- oilseed cake and meal
- soya beans cake and meal
- sunflower
- other oil seed cake and meal
- field beans
- field peas
- sugar beet pulp and molasses
- rice bran extractions
- meal (e.g. fish, poultry)

In Scotland, the role of distillery by-products, wheats and oats and, to a lesser extent, oilseed rape products, are important in the supply of protein into animal feeds. Data disaggregated to Scotland are not available. However, the UK as a whole relies on 47% (AIC, 2020) imported feedstuff, of which approximately 18% comes from the EU. Of the remaining imported feed stuffs, a significant proportion is in the form of soya.

The specific nutritional requirements for animal feed vary by species. As a result, there are demands for alternative protein sources which provide cost effective and nutritionally beneficial mixes of proteins, amino acid, and complementary nutrients.

The primary demands for animal compound feeds in Scotland include:

- dairy cattle
- beef cattle
- sheep
- pigs
- poultry
- fish

These species all demand different nutritional compositions and the specific requirements and raw feed materials used are based on the most nutritionally preferential mix of ingredients. Careful balancing of protein, carbohydrate and fats while excluding/minimising anti-nutritional elements present in some feedstuffs (those that either limit digestibility or palatability), as well as micronutrients and vitamins, is essential. Essential amino acids are often a critical consideration in diet composition, which is of particular relevance to monogastric species (pigs and poultry); this can drive demand for products derived from soya due to their preferential protein and amino acid profile (Stakeholder interviews, 2020).

- **Fish feed**

The current production of fish feed in Scotland is approximately 400,000 tonnes per annum with potential for this to increase to 600,000. Feed is used domestically for farmed salmon production but also exported to Ireland, England and the EU. Salmon feed has a high demand for protein (>35%) and oils/fats (>40%). Concerns for the sustainability of marine harvested fish meal have driven changing formulations of fish feed with increasing quantities of plant derived protein sources now being utilised. The high protein requirement has relatively niche sources including wheat gluten extract, soya protein concentrate and guar gum (Stakeholder interview 2020).

The use of faba beans with both a high protein and a significant starch content provides a favourable base for compound feeds and is an attractive feed raw material for this sector. However, although there is a demand for faba beans, only a small quantity of whole organic beans is sourced from Scotland. The lack of available dehulled and processed beans means they are currently sourced from England. There is also a demand for domestic grain legumes. However, it cannot currently be fulfilled.

- **Ruminant feed (cattle and sheep)**

Ruminant feed is based on a range of products that can be combined to meet the basic nutritional requirements. The most important products that are used in the production of compound feeds are:

- rapeseed meal
- distillery by-products
- sunflower meal
- wheat/barley
- soya

While peas and beans are certainly capable of providing the nutritional inputs required, the lack of supply and the relatively unfavourable cost mean they are generally unattractive when raw materials are being purchased. Compounds are designed months in advance with production runs requiring certainty of the inputs which are sourced in bulk. The high degree of uncertainty in year-round supply of domestic legumes can therefore add risk in their use.

- **Monogastric feed (pigs and poultry**)

Diet formulation for monogastric species such as pig and poultry require a careful balance of nutritional inputs, including essential amino acids such as lysine. They are also more susceptible to anti-nutritional elements which can lead to some inputs being unsuitable in high volumes, impacting the suitability of peas, beans and lupins (Kay 2014, stakeholder interviews, 2020).

The use of food co-products and soya provide a cost effective and preferential balance of nutritional inputs. Similar to the case for ruminant compound feed diets, the economic cost and the security/availability of supply are driving low demand for grain legumes in this sector. Alternative sources of protein are more cost effective, have greater availability, and, in the case of soya in particular, have a beneficial nutritional value above domestic grain legumes. These factors make them both economically and technically more attractive within monogastric diet formulation. The feed sector is conscious of the potential impacts of unsustainable production of soya; increasing pressure from consumers, farmers and politically, as well as increased awareness within the agricultural supply sector, is driving moves towards more sustainable sources of soya, including increasing production across the EU.

- **Human consumption**

At the UK level there has been a decline in the consumption of peas, beans and dry pulses in their traditional form since the 1970s; Figures 1, 2 and 3 provide the details of fresh, frozen and canned pulses. While this decline has continued for canned peas, the market for canned beans has stabilised since the late 1990s. Similarly, consumption of fresh beans and peas have stabilised since the early 1990s.

While insightful in the context of dietary preferences, these figures are not directly relevant to demand for Scottish legumes. However, the market for frozen peas and beans can offer direct relevance to Scotland. Current consumption is relatively stable with some indication of increased consumption of frozen peas across the UK.

The annual Family Food data (Defra 2020b) from the Living Costs and Food Survey run by Defra each year, captures data on the average consumption of food in UK households. Using this data the annual demand for frozen peas in Scotland has been calculated as approximately 9,000 tonnes per annum. Assuming an average yield of approximately 4.5 tonnes per ha for vining peas, the production of peas in Scotland equates to approximately 36,000 tonne per annum, far exceeding the current demand in Scotland. Production of vining peas in Scotland account for approximately 20% of the total UK production (PGRO, 2016). The UK is an important producer of fresh and processed peas, producing a net surplus.

Figure 1: Trend in consumption of fresh pulses 1974-2018, g/person/week. (source: Defra 2020b)

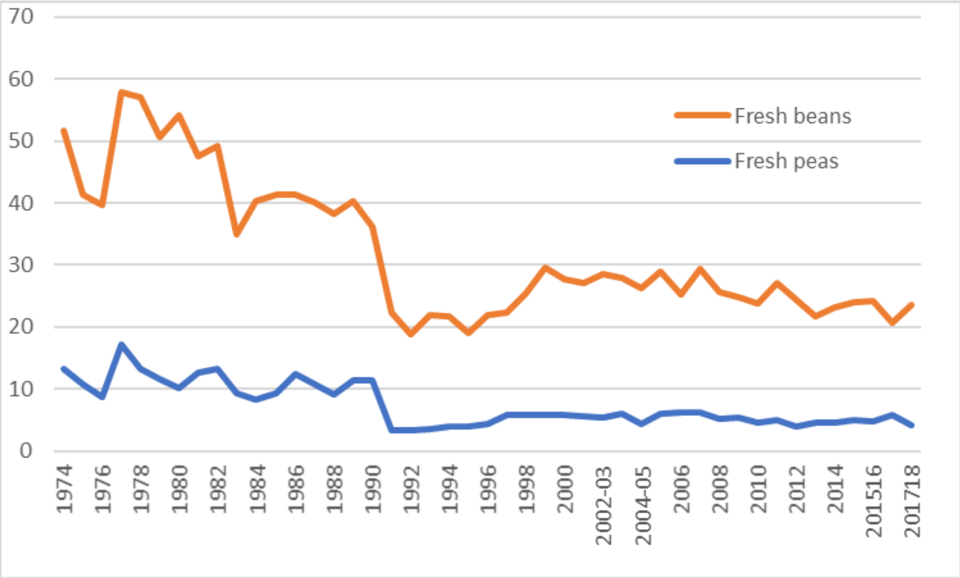


Figure 2: Trend in consumption of canned pulses 1974-2018, g/person/week. (source: Defra 2020b)

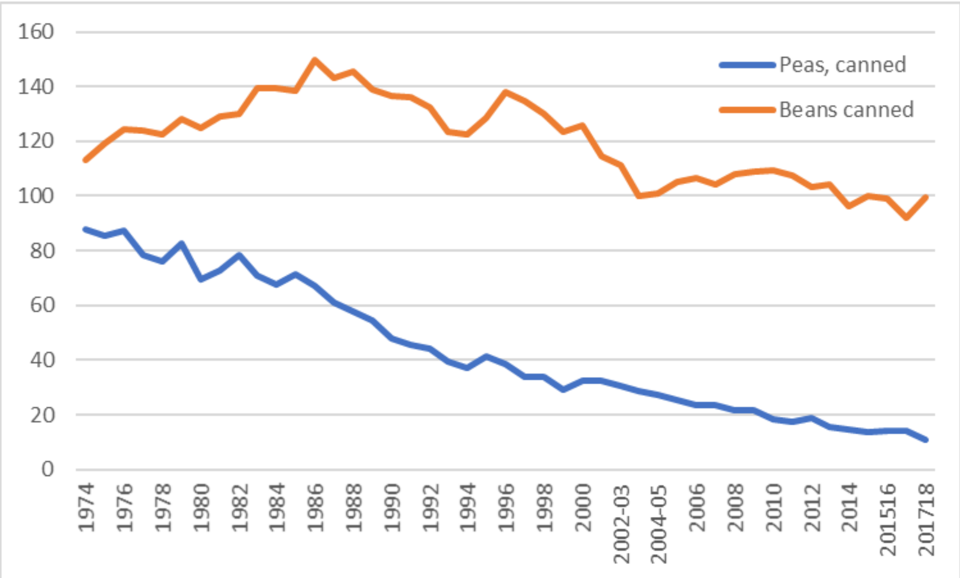
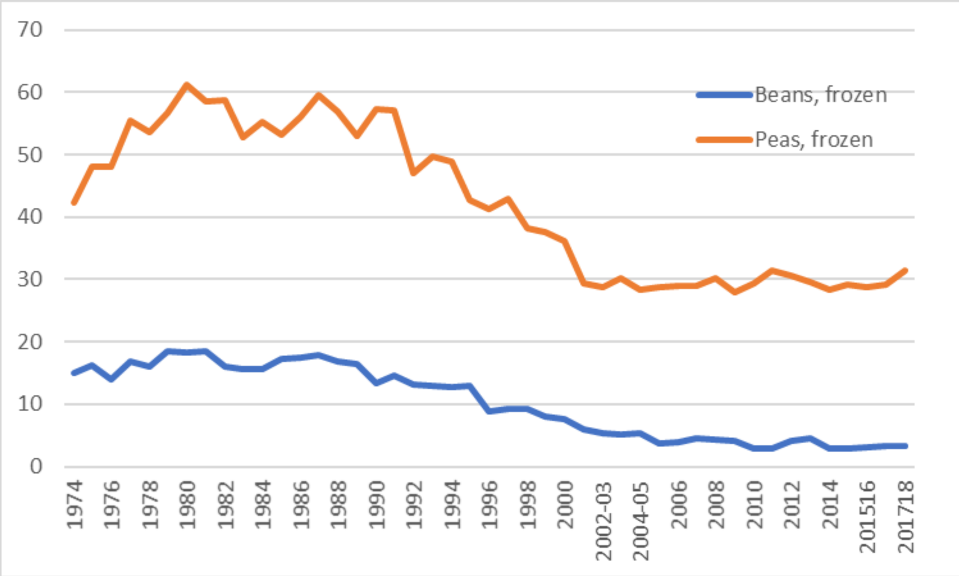


Figure 3: Trend in consumption of frozen pulses 1974-2018, g/person/week. (source: Defra 2020b)



While the fresh and processed pea market is dominant in the current production base for legumes in Scotland, recent change in the nutritional advice (Lancet, 2019) and increasing interest in vegetable protein are creating new markets for field beans and peas. Human consumption is already an important potential market for UK growers and receives a premium price, if the requisite quality can be met (Montriro et al., 2017). Data on the ultimate destination of Scottish field beans and peas are not available and so the extent of access to this growing market is not known. Similarly, the specific nature of demand for novel pulse-based products in Scotland is not available but, based on the study of Montriro et al., this will be an important and rapidly growing market. Grain legume production in Scotland does have some advantage in producing faba beans of good quality that can be used within the human market. The report by Montriro et al. identified very significant growth in the products utilising grain legumes. Communication from stakeholders confirmed expectations of significant interest in pulses as part of people's diets. This is further supported by market trends across Europe with Tesco indicating 300% increases in plant-based meat alternatives by 2025 while Deloitte (2019) predicts the European market for plant-based meat alternative will be worth €2.4bn by 2025, with significant expansion expected to continue.

3.1.2 Forage legumes/green manures

The majority of Scotland's agricultural land is used for the production of ruminant livestock. The area of improved grassland, including temporary grass and permanent pastures is approximately 1.32 million ha (Scottish Government, 2020). This land is used to provide direct grazing and saved forage through the production of hay and silage. Increasing the nutritional value of these forage sources can offer significant benefits to livestock production. In Scotland, this improved nutrition is achieved through the inclusion of clover and species such as vetch, peas and clovers within herbal and grass leys (Lüsche et al, 2014). The use of these more diverse and nutritionally dense mixed swards is increasing and, although there is no official data collected, reports from stakeholders confirm growing interest from growers and increased investment in seed mixes to establish these forage crops.

Improvements in the understanding of soil processes, including soil nutrient cycling, soil biology and physical structure have increased awareness and interest in the use of legumes within more diverse rotations. Many studies have confirmed the benefits

(Preissel et al., 2014; Watson et al., 2017; Legume Futures, 2014). Data on the increasing utilisation of legumes to provide regenerative functions for soil quality and function are not currently collected. However, stakeholders (both farmers, and input suppliers) report increasing utilisation of legumes as cover crops, green manures (legumes grown to fix atmospheric nitrogen and then incorporated into the soil to provide nitrogen for following crops) and companion crops/intercrops.

3.2 Supply – production of legumes

3.2.1 Grain legumes

The area of current production of grain legumes in Scotland is relatively small compared with global production (14.5% of tillage land) (Watson et.al) and European production (2.2%). The total UK production of legumes accounts for about 3% of the tillage areas (Defra, 2020a).

The current area of grain legume production in Scotland reported within the agricultural statistics is just 0.4% of the tillage area (Scottish Government, 2020b) for dry legumes (peas and beans). If this is combined with the area for human consumption, this still represents just 2.3% of the tillage area in Scotland in 2020.'

The area of the main legumes in Scotland is presented in Table 1.

Table 1: Area of legumes in Scotland (ha) (source: Scottish government, 2019)

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Protein peas	2,025	1,668	1,198	682	537	616	1,470	776	714	514	517
Field beans	4,728	5,268	3,738	3,789	2,891	2,765	4,045	3,002	2,993	2,033	1,803
Peas (canning, freezing or drying for human consumption)	6,296	6,549	6,276	6,553	6,559	6,922	7,029	7,540	7,808	8,140	8,142
Beans (canning, freezing or drying for human consumption)	899	1,011	996	1,193	1,153	1,018	1,469	1,789	1,767	1,813	1,800
Lupins (grown as forage)	509	284	199	140	104	114	86	43	27	5	*

*Note: no data presented in 2019 to prevent identification of respondents

Except for fresh and processed peas, the supply of grain legumes in Scotland is very low. Despite potential markets, there are elements of market failures which make grain legume production an unattractive option. Historically, grain legumes have been grown on larger areas. The reasons for the weak supply of grain legumes are discussed in more detail in Section 4.

3.2.2 Forage legumes

The inclusion of legumes (in particular clover species) is well accepted within Scotland, with clover included in approximately 95% of all grass seed mixes sold, indicating a well-established demand.

However, with no data on the extent of grassland of cropped area using legumes for forage or on the coverage and species of legumes present, it is not possible to comment more on the role of legumes in forage.

4 The opportunities and constraints for legumes in Scotland

This section takes in to account the findings of the literature review and stakeholder outputs to consider the reasons legumes are not grown more widely in Scotland. The evidence gained identifies many opportunities for legumes, with their potential to support multiple objectives for more sustainable agricultural systems.

The PESTEL and SWOT analysis presented in Table 13 (Appendix 3) and Table 2 highlight many benefits of increasing the production of leguminous crops in Scotland. However, the constraints relating to technical knowledge, varieties, market failure in the form of low demand, and low prices may need support to be overcome. Here we describe the main opportunities and constraints identified through these analyses.

4.1 Forage legumes

Utilisation of forage and clover species within grassland areas is prevalent across Scotland, with the benefits of legumes within grazed and saved forage well established (Peyraud et al., 2009; Baddeley, 2020; Lüscher, 2014). These include:

- reduced inorganic fertiliser use
- emission reductions (GHG and nitrate)
- lower production costs
- increased protein content of forage
- higher productivity – increased forage yield – improved conversion efficiency of plant to animal protein
- animal health and welfare benefits – bioactive secondary metabolites

While there are some potential agronomic constraints for the persistence of clovers within grass swards (lack of persistence and low pH), their use is widely adopted (multiple stakeholders, 2020). More detailed assessment of additional potential is complicated by the lack of specific data on the current state of legumes within forage. But evidence from stakeholders suggests that the benefits identified above can be further realised with improvements in the uptake of forage management, utilisation of saved forage and the application of both grazed grass and forage analysis to support better ration optimisation. An important factor identified by several stakeholders was the need for improved fertiliser practice for the various legume species, e.g. the need for macro-nutrients (such as phosphorus, potassium sulphur) and micro-nutrients (such as cobalt and molybdenum) which are important in the nitrogen fixation process.

Ensuring optimum soil fertility and crop nutrition is an essential component of the following objectives of growing legumes:

- optimising productivity and quality
- optimising protein content (and particularly amino acids) – application of sulphur to get the right N:S ratio for optimising DM yield and protein content.
- optimising potential to reduce N_2O emissions requires optimum NUE which, in turn, needs optimum soil fertility and crop nutrition / health

Greater awareness of soil analysis and the need for balanced nutrition to support legume establishment and growth are critical.

There is both poor current knowledge and limited practice in terms of the utilisation of soil analysis and the specific nutritional requirements for legumes. While there are some knowledge gaps, management of soil pH represents a real opportunity to support forage legume production. Many soils in Scotland have low pH; this can be a significant limiting factor for legumes (and is also a critical factor in wider nutrient availability).

Evidence from stakeholders also indicates potential to increase the use of whole crop legumes, intercropping (legumes and other crops usually cereals) and high biomass legume mixes as silage for saved forage. Harvesting grain legumes as whole crops may offer opportunities to support valuable crops while avoiding some of the difficulties of grain production (see Section 3.1.2).

4.2 Grain legumes

From the review of demand and supply factors above, it is clear that, although there are many very good drivers for grain legume production, there remains limited engagement both in their production (supply) and demand (active market development) within Scotland.

More detailed analysis of these factors is provided in the PESTEL (Appendix 3) and SWOT (Table 2) assessments

Economics is perhaps the most significant factor influencing the production of grain legumes in Scotland. While legumes can be relatively cheap to produce, prices for general traded grains are relatively too low for producers; other crops, such as oilseed rape and cereals, have far better economic return potential. On the counter side, while grain legumes do provide the nutritional requirements demanded by animal feed producers, their current cost disadvantages them when compared to alternative input sources, such as rapeseed meal or distillery by-products. The limited supply both in Scotland, and more widely across the UK, increases the risk in using them within compounding specifications.

Recent changes in the composition of fish feed does offer an opportunity (particularly in Scotland) for increased demand in faba beans. Reductions in the use of fish meals, associated with concerns for sustainable harvest of marine species, have led to an increase in the sourcing of vegetable proteins. Faba beans offer some advantage in the feed production process in that they can provide a good blend of starch (useful in the pellet composition) and protein, offsetting the need to source starch from alternative sources such as wheat.

A lack of production has limited investment in ancillary infrastructure in Scotland – there are no mills equipped to process peas and beans (dehulling, fractionation) which is required to provide products direct to feed companies. This lack of infrastructure will certainly limit the market both from a willingness to grow grain legumes perspective but also in terms of grain traders' willingness to purchase and trade them.

The cultivation of grain legumes in Scotland also poses some challenges to growers. Many stakeholders said the uncertainty in yield, difficulties in both establishment and in harvesting were key factors in their hesitancy to grow both peas and beans. When considered with the poor economic returns, many growers consider the production of grain legumes too uncertain to warrant the “hassle”.

The lack of investment in breeding and variety development has been identified as a factor exacerbating the advancement of production. This linked with agronomic factors, such as loss of some plant protection products, and a general poor familiarity with the requirements for growing grain legumes contribute to a general hesitancy to grow legumes.

Despite the apparent barriers to increased legume production, there is a generally high interest and optimism towards grain legumes, both from the farming community and the wider markets. Growing interest in processed legume products for human consumption with premium markets available (and advantageous conditions due to Scotland’s lack of Bruchid beetle) is reported by some growers. This premium market offers viable economic returns, offsetting some of the disincentives in general feed grade grain legumes.

The PESTEL analysis (Table 13, Appendix 3) highlights many benefits of increasing the production of leguminous crops in Scotland but the constraints relating to technical knowledge and markets may need support if they are to be overcome.

4.3 Strengths, weaknesses, opportunities and threats (SWOT)

The review of literature and the stakeholder interviews focused on identifying the key characteristics of legume production in Scotland. The PESTEL assessment summarises the factors influencing the production of legumes, including both opportunities and constraints along with mitigations. The strengths, weaknesses, opportunities and threats (SWOT) coming from the PESTEL assessment have been identified in Table 2.

Table 2: Strengths, Weaknesses, Opportunities and Threats for Legumes production in Scotland

Strengths	Weaknesses
• Environmental benefits for GHG, soil, water and biodiversity are well established. • Can support more diverse rotations – reducing costs and artificial nitrogen fertiliser inputs. • Scottish condition offers some advantage for food grade bean production (low pest pressure). • Forage legumes accepted and widely used. • Can support improved efficiency in livestock production through improved forage and grazing quality. • Reduces the need for artificial fertilisers thereby reducing greenhouse gas emissions. • Reduced chemical input can benefit biodiversity. • Fresh Pea production – specialised and well established with significant infrastructure already in place.	• Growing conditions can be challenging for both establishment and harvest (wet weather, late maturing). • Perhaps most significantly, market demand for grain legumes is low due to competition from other alternative and cheaper sources. • Confidence in production is low. • Susceptible to weather variations – can result in variable yields. • Poorer economic performance compared to other crops e.g. cereals and oilseed rape. • Soil pH can be an issue in Scotland.

Opportunities	Threats
• New markets and increased awareness of the benefits of legumes. Pea protein consumption doubled globally between 2015 and 2020 with the rise in plant-based meat alternatives • Significant increases in human consumption market projected. • Decreased fertiliser use across a rotation. • Cost savings through reduced fertiliser use. • Decreased GHG emissions across a rotation. • Global pressure on other protein sources could increase demand (improve price and financial viability). • Improved self-sufficiency in domestic protein sources (both forage and grain). • Human consumption with premium price could support increase production. • New production systems (e.g. intercropping, new species and varieties). • Improved soil fertility. • Soil Health benefits driving interest and more holistic perspective, this is supporting reinvigorated interest in legumes.	• Loss of production technologies (varieties, plant protection products, advice and agronomy support). • Cultural resistance to growing grain legumes (farmers have had poor experiences; whole sector is risk averse so will not try to grow them). • Poor economic performance – Brexit impacts could exacerbate these in particular the premium human consumption market. • Disease spread – bruchid beetle, chocolate spot, foot rot and damping off. Rhizoctonia in the soil is a major factor, seed treatments no longer available. • Vining pea (fresh peas/beans) require land to be free of any pea or bean crop for 6 years prior to establishment. These areas of land are already well established around the processing plants. Increases in combinable peas and beans in these areas could significantly impact upon this production.

4.4 Evidence gaps

Legumes are viable options for both forage and grain-based production in Scotland. Current varieties of vining and field beans and peas have been grown successfully in Scotland for decades. The drivers for their production and consumption are in many ways very simple and relate to economic performance and risk management. he benefits and advantages of legumes are clear and well evidenced; this review has identified a wealth of evidence both from stakeholders and literature.

There are few gaps in the evidence relating to the study. One gap relates to the specific characteristics of legume prevalence within the grassland area of Scotland. We have found evidence for the widespread utilisation of legume mixes within improved grassland but have been unable to quantify this. While this information may help in the development of future policies, it has not been a significant limitation to this study.

4.5 Suitability of land for legume crops

A review of the suitability of land for legume crops production was completed. The review and analysis considered the current situation based on legume crop growth conditions and constraints. Legume crops that had the potential to be grown in Scotland were selected for analysis following a literature review, with crops defined as follows:

- forage legumes
    - white and red clover
    - common vetch
    - lupins
    - lucerne
- grain crops
    - peas
    - beans
    - faba beans
    - soya beans

Within the review, the main constraints to growth of legumes were found to be rainfall and temperature. Access constraints, soil type, and land use and availability also limit areas for growth. A list of technological and environmental constraints is given in Appendix 4 (Table 14). The constraints in the list can be reflected, to some extent, in a ruleset for quantifying the area of land that is agronomically suitable for legume crop growth. Some of the constraints can be used in an analysis of spatial data, such as climate, soil type and topography (gradient). Other constraints cannot be used in an analysis of the spatial data, such as lack of advice, limited availability of pesticides and machinery limitations; these do not influence the area of agronomically suitable land but will modify the extent and uptake of legume crop growth.

The main sources used in the review were:

- expertise of the project team based on industry experience
- Feedipedia encyclopaedia of animal feeds (2019)
- The practical effectiveness of nitrogen-fixing crops (Iannetta et al., 2019)
- Combinable protein crop production report (Wright, 2008)
- Legume Futures Report 1.3 (Stoddard, 2013)
- Legume Futures Report 1.6 (Reckling et al., 2014)
- Crop production in the East of Scotland (Hay, 2000)
- Effects of cold temperatures on winter annual legume cover crops (Thurston, 2019)
- Nitrogen fixing crops SRUC (Baddeley, 2020)

The full list of sources can be found in the References at the end of the report.

4.5.1 Baseline land cover availability

Details of the datasets and rulesets used for this analysis are found in Table 16.

The resulting areas of suitable land theoretically available for legume crop cultivation are presented in Table 3 (upper estimates). Calculations to derive these areas only consider the constraints in Table 16 where spatial data was available (e.g. soil type, slope angle and climate). Errors on each area are taken to be ±5% and are quoted in Table 4. Areas under 10 m^2 were removed from the total suitable land area as these were considered too small to establish agricultural legume growth.

Table 3: Areas of land suitable for legume crop cultivation

Crop type	Area of suitable land (ha)			
	Theoretically suitable total land area	**Suitable land area within LCA classes 1 to 3.1**	**Suitable land area within LCA classes 3.2 to 4.2**	**Suitable land area within LCA classes 5.1 to 5.3**
Forage legume crops	1,224,783 ± 61,239	470,902 ± 23,545 (38% of total area available)	600,594 ± 30,030 (49% of total area available)	153,286 ± 7,664 (13% of total area available)
Grain legume crops	723,600 ± 36,180	416,014 ± 20,801 (57% of total area available)	307,586 ± 15,379 (43% of total area available)	---

The analysis shows there currently exists a large area of land which is **theoretically** suitable for legume crops growth. Generally, the most suitable land lies in the east of Scotland and the lowlands. However, the mapping shows that there are currently small parcels of opportunities along the coasts in the west and north of Scotland. Forage legume crops have a greater theoretical land availability, with additional land in the central east areas, in comparison to grain crop area availability, due to the inclusion of the improved grassland (Classes 5.1 to 5.3) land classification within the analysis.

As noted, the land areas represent a **theoretical** upper limit of what is available. The availability of this land will be limited by a range of other factors, for example, the constraints not covered by spatial data (Table 14) and the need for land for other uses, such as fodder production, forestry, energy crops etc.

In order to understand how this suitable land area for legume crops changes, the upper limit of land available has been presented as a total and separated within the LCA categories considered within this assessment. Percentage totals for each of these areas against the **theoretically** suitable total land area are also presented in brackets in Table 3.

4.5.2 UK Climate projections

The study requires an understanding of the future availability of suitable land for legume crops due to climate change. Within this project the Met Office's UKCP18 (Lowe et al., 2018) climate predictions were used to derive future changes in rainfall and temperature. Although there are a range of time periods provided within the UKCP18 predictions, a representative subset of these were used to give a good temporal coverage out to 2100, namely 2040-2059, 2060-2079 and 2080-2099. Emissions scenarios have changed from the UKCP09 predictions and are now presented as Representative Concentration Pathways (RCPs) (UKCIP18, 2018), specifically RCP 2.6, 4.5, 6.0 and 8.5. These represent radiative forcing targets and are linked to different climate outcomes. The RCP 6.0 was deemed to be most suitable for this project as it represents a 2.8°C increase in global mean surface temperature and is located between the low to medium emissions scenario provided in UKCP09, representing the mid-range of the forecasted climate changes. As such, the RCP 6.0 pathway, with a 50% probability of occurrence for the area of East Scotland were selected as the key data. The area of East Scotland was selected specifically as it covers the vast majority of the land suitable for arable crop growth in Scotland. The individual future predictions of climate change for rainfall and temperature provided by the UKCIP guidance and used in the report are presented in Table 4.

Table 4: UKCP18 predictions for changing mean summer rainfall and mean summer temperature for Eastern Scotland for the RCP 6.0 emissions scenario at 50% probability for the three selected periods.

	Time period of scenario		
Climate variable	**2040-2059**	**2060-2079**	**2080-2099**
Mean summer temperature (°C)	1.1	1.8	3.0
Mean summer precipitation change (%)	-7	-13	-22
Mean winter precipitation change (%)	10	10	15
Average of mean summer and winter precipitation changes (%)*	1.5	-1.5	-3.5

* The average of mean summer and winter precipitation changes is not taken from the UKCIP18 reporting but are calculated from the mean summer

The climate predictions for mean summer rainfall and temperature for 2040-2099 (Table 4) were applied to the processed 1981-2000 baseline rainfall (CEH GEAR, Table) and temperature datasets (CEH CHESS, Table), downloaded from CEH. We selected data from the resulting datasets using the critical temperature and rainfall thresholds detailed in Table 16.

For the purposes of this research, it was found that the most appropriate critical thresholds for leguminous crop growth were focussed on annual total rainfall ranges. As predictions for change in this value are not catered for in the UKCP18 data, we have assumed that predictions of change in annual rainfall total is approximated by using the average of the mean summer and mean winter change in rainfall (highlighted in grey in Table 4).

These datasets were subsequently used to exclude areas of land outside the suitable climatic ranges from the baseline suitable land areas created in Step 6 (see Section 8.5.3). These actions generated datasets of suitable land areas under climate change projections for the periods 2040-2059, 2060-2079 and 2080-2099.

Full details of the UKCP18 and the selected climate change scenarios and a more detailed methodology are presented in Appendix 5.

4.5.3 Impacts of changing climate on legume crop growth areas

The resulting areas of suitable land available for each legume crop in the future (with respect to climate change) are presented in Table 5, along with percentage change in land area against the baseline. Errors on land areas are taken to be ±5%. We have not provided for any additional errors associated with climate change uncertainty.

Table 5: Predicted areas of suitable land for each legume crop in 2040-2059, 2060-2079 and 2080-2099

	Area of suitable land (ha)					
Crop type	**2040-2059**	**Change against baseline**	**2060-2079**	**Change against baseline**	**2080-2099**	**Change against baseline**
Forage legume crops	1,221,487 ±61,074	100% of baseline	1,261,739 ±63,087	103% of baseline	1,313,028 ±65,651	107% of baseline
Grain legume crops	678,593 ±33,930	94% of baseline	776,201 ±38,810	107% of baseline	838,812 ±41,941	116% of baseline

Graphical exports of land available under baseline and climate projections are presented in Appendix 5 (Figure 6 and Figure 7).

The analysis shows that under the UKCP18 climate predictions for Scotland areas of **theoretically** suitable land for forage legumes will remain constant with the baseline in 2040-2059 and increase thereafter, and for grain legume crops will slightly decrease in 2040-2059 and subsequently increase in 2060-2079 and 2080-2099. The majority of the expansion of legume crops occurs in the central/east of Scotland, with small increases to the islands and coastal areas.

Projected climate changes are expected to provide increased availability of land for both grain and forage leguminous crop growth. This is due to a projected reduction in rainfall, with projected increased temperatures having limited impacts as the majority of Scotland is already within the optimal growth range (<10 to >25°C) and remaining in the optimal growth range over the climate projection timescales.

Leguminous crops are limited by excessive rainfall, with the growth of the majority of crops analysed within this report limited at a maximum of 1000-1200mm annual rainfall (Appendix 4, Table 15: Crop constraint parameters). A reduction in annual rainfall would potentially allow for production of increased varieties of leguminous crops, such as soya beans, which have optimal growth at 500-850mm (Feedipedia, 2019).

4.6 The potential to increase self-sufficiency in protein

The analysis of evidence as discussed in Sections 3, 4.2 and 4.5 above identify significant opportunities for future increased production/advancement in leguminous crops across grain areas in Scotland. These would increase the supply of legumes and also reduce the need to import additional protein sources.

4.6.1 Potential for supply expansion

- New markets and changing consumer demands are creating opportunities for premium markets (whole foods, pulse-based flours, high-value protein extractions). Scottish growers should be able to access these markets. The potential for these higher added value markets is likely to improve the economic attractiveness of grain legumes.
- Increasing awareness and evidence for the benefits of systems such as intercropping, whole crop forage and green manures within rotations – use of

legumes within extended rotations should support more holistic assessments of legumes as part of more sustainable rotations. This approach would engage more farmers and support increased area of grain legumes.

- Increasing awareness of wider environmental concerns, such as climate change and sustainable protein, are influencing market specifications. These will drive demand for alternatives.
- Reductions in supply of non-legume protein sources (e.g. oilseed rape meal) and reduced use of soya imports could influence the price of domestic legumes providing more encouraging economic conditions.
- The area of grassland including legumes is likely to be relatively high. Although there is a lack of data to confirm this, there is potential for better management and utilisation of legumes within grassland and for more novel approaches to both grazing and saved forage.

4.6.2 The effect on self-sufficiency

There are available markets which can utilise grain legumes in Scotland, including a growing interest in current supply for the fish feed sector. The technological and economic constraints identified in Section 3 limit the ability to realise the potential for increase self-sufficiency in proteins in Scotland. However, the following key points are worth highlighting:

- Better use of forage analysis and understanding the potential to improve the protein balance of forage would reduce the demand for imported protein used in animal feeds. Better utilisation of forage-based legumes has been shown to offer significant advantages for economic performance, productivity and the environment (including GHG emissions).
- Increased utilisation of legume proteins may offset the import of protein sources such as soya or sunflower-based products. However, as these represent less than 50% of the current ingredients for animal feed this replacement is uncertain. The preferential nature of soya for monogastric diets suggests the use of domestic legumes is likely to focus on ruminant, human consumption and fish feed use. Ruminant feeds use a relatively small proportion of soya, so it is likely that increases in legume production in Scotland could offset products such as rapeseed meal, distillery by-products or imported sunflower products. Quantification of the trade and import responses to increased legumes would require a detailed econometric study which was outside the scope of the study.
- A very small area and volume of grain legumes is produced in Scotland; any increases in this area would have the potential to increase self-sufficiency in both human and animal diets. Shortening the supply chains even, by reducing the imports of feed inputs from the rest of the UK, would help realise the benefits from legumes in terms of the wider environment.

5 The potential to reduce GHG emissions

5.1 Principles and pathways

The main pathways to GHG emission changes considered here, through substitution of non-leguminous crops with leguminous crops, are:

- changes in nitrous oxide emission from soil (through changes in nitrogen fertiliser use and crop residue returns to the soil); and
- a decrease in emissions through lower demand and production of nitrogen fertiliser; these emissions occur outwith Scotland, but we consider them because they are large.

We limited our consideration of GHG emissions changes to these two pathways, both of which are directly related to the quantities of nitrogen fertilisers applied.

Emissions changes from other sources on cropland are expected to be minor (e.g. emissions from fuel combustion during field operations). Indirect effects on GHG emissions are difficult to quantify and will include consideration of crop displacement (e.g. if a legume crop replaces wheat, then more wheat may be grown elsewhere with associated emissions). This aspect is not included in our emissions change estimates because of the complexities. It is our opinion that this is not a major concern because legume grain crops will supply similar markets to the cereals that they displace. Improved productivity within the entire rotation may decrease the shortfall in supply of displaced crops while increased demand for non-meat protein sources may decrease demand for displaced crops, offsetting some of the indirect impacts.

Our analysis was based on a review of relevant literature and the application of findings to the scenarios described below.

5.2 Scenarios

5.2.1 Rotational complexities

Legume crops fix atmospheric nitrogen, through the action of symbiotic bacteria. They make nitrogen available to the plants and decrease the need for supplementary nitrogen fertilisers to achieve an economic yield. The nitrogen introduced into the farming system in this way benefits the legume crop, and also the following crops. Residual nitrogen remains in the soil (and in crop residues) and is used by the subsequent crops, decreasing their requirement for nitrogen fertilisers. Therefore, the estimation of the greenhouse gas consequences must be made across the crop rotation, to include crops that follow the legume crops.

The GHG emissions effect of growing legumes in a rotation is highly complex for several reasons, including:

- rotations are highly variable;
- the management of crop residues, particularly for following cereal crops, is variable;
- the mineralisation of nitrogen in crop residues and other organic matter is variable and is dependent on environmental conditions;
- the carry-over to the next crop of available nitrogen in the soil is dependent on environmental conditions; and

- the nitrogen demand varies between following crops, related to crop species and yield.

5.2.2 Scenario definitions

We define two main scenarios to illustrate the effects of increasing the area of legume crop production in Scotland:

Scenario 1 (grain legume increase): change from current production area of legume crops on tillage land (land that is annually cultivated) to an increased area of legume crops that represents one crop in a five-year rotation (i.e. 20% of the tillage crop area).

Scenario 2 (forage legume increase): increase inclusion of legume species (mainly red or white clover species) in grassland that is re-seeded, from the current area to the theoretical maximum (i.e. all grassland that is re-seeded includes clover).

5.3 Greenhouse gas mitigation

5.3.1 Substitution of nitrogen fertiliser

- **Scenario 1**

To illustrate the potential for decreased nitrogen fertiliser use, we estimated the quantity of N fertiliser applied to a theoretical five-year rotation that included winter wheat, winter barley, winter oilseed rape, winter oats and spring barley. We used the average field rate (kg/ha) for these crops in Scotland, taken from The British Survey of Fertiliser Practice, Fertiliser Use on Farm Crops for Crop Year 2019 (BSFP, 2019), Table SC1.1. We then replaced oilseed rape in the rotation with field beans and compared the nitrogen applications across the rotation. We used Technical Note TN651: Nitrogen recommendations for cereals, oilseed rape and potatoes (SRUC, 2013) to adjust the nitrogen application to the crop following field beans, compared with the nitrogen application when the same crop followed oilseed rape.

Overall, the nitrogen applied per ha across a rotation without field beans included was 128 kg/ha, and with field beans was 97.2 kg/ha, an annualised nitrogen saving of 30.8 kg/ha. This is a saving of 24.1%, which is comparable with other published estimates. For example, Squire et al. (2019) found a saving in N inputs following 20% legume inclusion (i.e. a legume grown one year in five) of 21.4 to 23 kg/ha. Jeuffroy et al. (2013) found a decrease in N_2O emissions by 20–25% through including one pea crop in a three-year rotation, indicating likely decreases in N inputs by a similar percentage.

We scaled up our estimate of N saving per ha to a theoretical maximum for Scotland, by taking crop area data from the June Agricultural Census 2020 Scottish Government 2020b). We added up the areas of annually cultivated legume crops (i.e. those grown on arable land, including peas and beans for livestock feed or for human consumption, but excluding legumes in pasture) and estimated the area of tillage crops (annual crops) that could include a legume crop for one year in five, and subtracted this area from the total for tillage crops. This area could have adjusted rotations to include legumes, and we scaled our estimate of N savings to this area. The data are shown in Table 6.

Table 6. Crop area data and nitrogen savings by introducing legumes into a rotation, assuming a legume crop one-year in five. Crop area data are for 2020, from Scottish Government (2020b).

Variable	Value	Units
Total area of tillage crops	584,061	ha
Proportion of tillage crops that are legumes	0.0210	
Equivalent area of tillage crops with 20% legumes	61,309	ha
Equivalent area of tillage crops with no legumes (area for scaling up)	522,752	ha
Nitrogen saving per ha	30.8	kg N
Theoretical maximum nitrogen saving scaled up to Scotland	16,101	tonnes N

- **Scenario 2**

Inclusion of clover in grassland decreases the need for nitrogen fertiliser because atmospheric nitrogen is fixed by the clover through the action of symbiotic bacteria, making nitrogen available to the clover and to grasses in the sward. The use of nitrogen fertiliser can be substituted if the area of grassland with clover can be increased. Our stakeholder consultation indicated that white clover is widely present in grassland that is not periodically reseeded, and there is little or no scope to increase the proportion of this grassland that includes clover.

For grassland that is re-seeded, our stakeholder consultation provided information on the seed mixes used for re-seeding. About 95% of all grass ley seed mixtures sold in Scotland contain clover. There will also be some re-colonisation of re-seeded grassland by clover. This informs our opinion that the percentage of improved, re-seeded grassland in Scotland that contains legumes is close to, or at, 100%, and there is very limited, or no, scope for increase. For this reason, we have not presented estimates of GHG savings from increasing the area of improved grassland that contains clover.

We acknowledge there may be room for improvement in the way forage legumes are managed, to optimise the value of clover within a sward, but we have no data on current performance to allow us to estimate improvement benefits in terms of reduced nitrogen fertiliser inputs.

5.3.2 Effects per unit of land area

For Scenario 1, we estimated the nitrous oxide emissions change for 1 ha of land using the nitrogen saving per ha (Table 6) and the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Tier 1 methodology (IPCC, 2006). We also estimated the GHG saving from decreased fertiliser manufacture using an emission factor from Hoxha and Christensen (2019) for ammonium nitrate. Data are presented in Table 7.

Table 7. Scenario 1: GHG emissions decrease for 1 ha of land.

Variable	Value	Units
Nitrous oxide emissions decrease for 1 ha	0.206	t CO_2e/ha/yr
Emission factor for ammonium nitrate	3.32	kg CO2e per kg N
GHG emissions decrease from decreased fertiliser manufacture, for 1 ha	0.102	t CO_2e/ha/yr
Total GHG emissions decrease for 1 ha	0.308	t CO_2e/ha/yr

5.3.3 Effects at a Scotland level

We scaled up our estimate of GHG emissions decrease to a theoretical maximum for Scotland using the ‘equivalent’ area of tillage crops with no legumes in the rotation, as given in Table 6. A theoretical maximum estimate of the GHG emissions decrease for Scenario 1 is given in Table 8.

Table 8: Scenario 1: GHG emissions decrease for Scotland

Variable	Value	Units
Nitrous oxide emissions decrease	107,441	t CO_2e/yr
GHG emissions decrease from decreased fertiliser manufacture	53,438	t CO_2e/yr
Total of nitrous oxide and fertiliser manufacture GHG emissions decreases for Scotland	160,880	t CO_2e/yr

As context to the estimates in Table 8, the emissions savings are given as percentages of GHG emissions values for Scotland in Table 9. The Scotland data are from the Devolved Administration GHG Inventory 1990-2018 (Thistlethwaite et al., 2020). The percentages in Table 9 show that the maximum potential GHG savings from increasing the legume crop area on tillage crop land to one crop in five (20% of the area) would be 1.4% of agriculture emissions in Scotland, taking account of savings in nitrous oxide emissions from soil. If we also take account of GHG emissions from fertiliser manufacture, that occur outwith Scotland, the maximum potential GHG savings increase to 2.2%.

Table 9: Greenhouse gas emissions savings as percentages of inventory emission values. LULUCF = Land Use, Land Use Change and Forestry. Total Scotland emissions include international aviation and shipping.

Variable	Value
Nitrous oxide emissions savings, percentage of nitrous oxide emission from agricultural soils	6.0%
Nitrous oxide emissions savings, percentage of agriculture emissions	**1.4%**
Nitrous oxide emissions savings, percentage of agriculture + LULUCF emissions	5.2%
Nitrous oxide emissions savings, percentage of total Scotland emissions	0.26%
Nitrous oxide + nitrogen fertiliser manufacture emissions savings, percentage of nitrous oxide emission from agricultural soils	9.0%
Nitrous oxide + nitrogen fertiliser manufacture emissions savings, percentage of agriculture emissions	**2.2%**
Nitrous oxide + nitrogen fertiliser manufacture emissions savings, percentage of agriculture + LULUCF emissions	7.9%
Nitrous oxide + nitrogen fertiliser manufacture emissions savings, percentage of total Scotland emissions	0.39%

5.4 Timeframe

The timeframe for increasing the proportion of legumes in land used for tillage crops will depend on many factors related to demand and economic performance. These are covered in Section 3.

6 Conclusions

6.1 Current production and trends

There has been a historical decline in the grain legume area in the EU, and there is a low level of production in Scotland (2.3% of the tillage crop area).

Use of legumes within forage is an accepted practice in Scotland and large areas of improved grassland benefit from their inclusion. There is little scope for an expansion in the area of legumes in pasture.

6.2 Availability of land

There is a large area of land which is **theoretically** suitable for legume crops growth. Generally, the most suitable land lies in the east of Scotland and the lowlands. However, Scotland's climate can pose some agronomic issues for grain legume establishment and harvest, leading to a perception among some farmers of poor crop performance.

Climate change is not expected to have a major effect on the area of land that can support legume crops in Scotland. Under the UKCP18 climate predictions for Scotland, the area of **theoretically** suitable land for forage and grain legume crops will decrease slightly in 2040-2059 and increase thereafter.

6.3 Greenhouse gas emissions

The main pathways to GHG emission changes through substitution of non-leguminous crops with leguminous crops, are:

- changes in nitrous oxide emission from soil (through changes in nitrogen fertiliser use and crop residue returns to the soil); and
- lower emissions from manufacture of nitrogen fertiliser (occurring outwith Scotland).

Including legumes in crop rotation, one year in five, could lead to an annualised nitrogen saving of 30.8 kg/ha. This is a saving of 24.1%, and 16.1 kt for Scotland. The savings in GHG emissions are 107.4 kt CO_2e/yr, rising to 160.8 kt CO_2e/yr when fertiliser manufacture GHG emissions (outwith Scotland) are included. This is equivalent to 1.4% of Scotland's agriculture emissions, rising to 2.2% when fertiliser manufacture GHG emissions are included.

6.4 Market and other constraints and opportunities

The UK is reliant on imports to provide 47% of protein sources used in animal feeds. With greater political and public awareness of the need for sustainable protein, the importance of domestic protein sources will increase. Due to the technical nature and diverse range of potential ingredients used in animal rations, we do not anticipate self-sufficiency in protein sources to be a viable opportunity. However, increased inclusion of domestically sourced proteins is achievable.

Economic conditions for both demand and supply are key influences on the area of legumes grown. From a demand perspective, as an ingredient in animal feed, legumes are too expensive. From a grower's perspective, the price is too low and other cropping options give higher and more reliable returns. However, new markets for human food ingredients and growing demand in the fish feed sector could offer opportunities for Scottish growers.

There are a range of technical and logistical limitations which depress the market for grain legumes. These may require some intervention but should not be significant, long-term barriers to increases in legume production. A lack of production has limited investment in ancillary infrastructure in Scotland – there are no mills equipped to process peas and beans (dehulling, fractionation), which is required to provide products direct to feed companies in Scotland. This lack of infrastructure limits the willingness to grow grain legumes as well as the willingness of grain traders to purchase and trade them.

There are cultural factors which influence farmers' decisions: perceived poor performance of grain legumes in Scotland has suppressed the area cropped. However, increased awareness amongst the industry of the potential of legumes to support more sustainable rotations, aid soil health and help manage disease and "regenerate" land are increasing interest in legumes (both grain and forage species).

Supporting improved knowledge, expertise and technologies (varieties and agronomic requirements) would help to increase performance, acceptance and success of grain legume performance under Scottish conditions.

6.5 Gaps in available information

6.5.1 Clover content of grassland sward

It is known that there is currently a wide adoption of legumes such as clover in grassland. However, there is little information available on how extensive this uptake is and, as such, how much opportunity there is to expand further the adoption of forage legumes. Work involving Jeremy Wiltshire (from the delivery team) in Eory, V., MacLeod, M et al. made the assumption that 44% of temporary and permanent grasslands had legume mixtures in Scotland in 2017, based on the Countryside Survey. However, the clover content in these swards varied due to different sowing rates and clover persistency. The opportunity to increase legumes in grassland was therefore assumed to be 56% on temporary grasslands in Scotland. However, as permanent grasslands are reseeded less frequently and managed more extensively, it was assumed that there is a 50% lower applicability on those land areas.

6.5.2 Farmer attitudes/willingness to increase grain legume cultivation to a 1 in 5 rotation

The study did not include any attitude testing of farmers; a survey of farmers and an evaluation of what factors would need to be addressed to achieve this goal would be valuable.

6.5.3 Lack of research to better understand balanced nutrition for legumes

There is limited research into the agronomic requirements for growing legumes. While many perceive the need to apply little or no nitrogen as the primary benefit of legumes, this often leads to a lack of attention to the wider nutritional requirements and soil nutrient status. Agronomic support for legume production is, therefore, not as advanced as for some more prevalent crops. Supporting research and knowledge exchange is required to ensure the impacts of nutrient deficiency are avoided.

6.5.4 Little research undertaken to identify new varieties suited to the Scottish conditions

Due to the lack of uptake of grain legumes in recent years, there has been little interest in investing in plant research to develop new varieties better suited to the Scottish climate. The two are highly interdependent and without intervention to support the research will continue to form a negative feedback loop.

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8 Appendices

8.1 Appendix 1: literature review details

8.1.1 Sources searched

Searches covered relevant peer-reviewed journal articles, grey literature (e.g. national and international government reports, industry and NGO studies, theses and dissertations) and unpublished evidence (e.g. reports or presentations and internal documents).

We searched the following sources:

1. Reference lists of publications known to the project team.

2. Science Direct
   Provides subscription-based access to a large database of scientific research.

3. Google Scholar
   Our experience is that careful use of search terms in Google Scholar returns almost all papers identified using other databases.

4. ResearchGate
   ResearchGate is a social networking site for researchers, allowing them to share papers, communicate and find other researchers. We have found this to be a useful way to obtain papers that are not otherwise available to us.

The literature review was supplemented by a stakeholder consultation and by collation of data from government and industry statistics, relating to the areas of crops grown by species, and the use of grain legumes in animal feedstuffs and the human food supply chain.

8.1.2 Key words, terms and search strings

Table 10: Search words and terms.

Words and terms	Notes
legume	Also: other names for this group of plants including: leguminous, Leguminosae, Fabaceae Caesalpiniaceae, Fabaceae, Mimosacae, Papilionaceae
grain legume	
pulse	
pea	Also the scientific name, and sub-types such as vining peas
bean	Also the scientific name, field bean, fava bean, faba bean
clover	Also the scientific name

Words and terms	Notes
lupin	Also the scientific name We also checked for developments in the varieties of other legumes not widely grown in the UK, such as lentils.
protein crop	
nitrogen-fixing	Also organic nitrogen
limitations	Combined with other terms above
potential	Combined with terms above
climatic zone	
self-sufficiency	
greenhouse gas emissions	GHG
supply	
demand	
Scotland	Also we will look for relevant studies on legume crops in the UK and other northern European countries.
review	May be included to prioritise review publications

Search strings are combinations of search words and terms using linked by Boolian operators (and, or, not etc.) and proximity operators (with, near etc.), and using parentheses to customise search terms further.

Search strings were developed iteratively during the searching.

Example:

"grain legume " OR "[list of terms used to describe grain legume crops, separated by OR]" AND “limitations” or “potential” or “climatic” AND “Scotland”

8.1.3 Screening criteria

Screening of search results is an important step to screen out papers not relevant to (e.g.) Scotland and farming. We screened papers initially on title, and accepted papers were then screened again using the abstract or summary.

8.1.4 RAG rating

We used a red, amber, green (RAG) rating to indicate quality. Where a study uses unreliable data sources or limited sources and the method is not robust, the quality of data was given a red rating. Where the work is peer reviewed, with well validated (actual) data and the method used is robust the source was rated good quality (green). Sources that are generally good quality but use assumptions or limited data were ranked amber.

Table 11: RAG rating criteria.

Description	Rating
Quality	
Peer reviewed journal, sound data sources and methodology	Green
Published research from the EC or international research funders, sound data sources and methodology	Green
Government funded research reports, sound data sources and methodology	Green
Research funded by NGOs (e.g. AHDB), sound data sources and methodology	Amber
Work is unreliable because of unreliable data sources, or limited sources, or because the method is not robust	Red
Privately funded research reports	Red
Information from websites, blogs etc., of unknown quality	Red
Relevance	
Geographic: Scotland Timeframe: within last 10 years	Green
Geographic: UK or similar climate (North-west Europe (not UK), parts of North America with similar climate) Timeframe: within last 20 years	Amber
Geographic: Not similar climate to the UK, outside north-west Europe and parts of North America with similar climate Timeframe: older than 20 years	Red

8.2 Appendix 2: stakeholder consultation

The role of legumes both in Scotland and more widely can be complex to understand. The benefits for the environment and climate mitigation have been widely recognised as having the potential to support alternative approaches to crop rotations and agronomy. This review sought to understand both the technical opportunities for leguminous crops (a literature and land capability review with technical analysis) but also the drivers, barriers and human factors which influence the real-world potential of leguminous crops. Critical to understanding these more dynamic and complex factors is the insight from the stakeholder consultation. The stakeholder consultation also supported the identification of additional literature sources, including grey literature and unpublished reports.

The focus of the stakeholder consultation was on the current supply and demand factors influencing legumes – primarily looking at the current uses and demands for grain legumes but also seeking to understand the role of legumes within grassland systems.

8.2.1 Key areas of inquiry with stakeholders:

- What are the main demands/uses for protein crops in Scotland?
- What sources of protein are currently utilised in Scotland?
- How are they used?
- Where are they sourced?
- What constraints are there to sourcing and using proteins sources within Scotland?
- Are you aware of any agronomic limitations?
- What do you see as the main barriers to increased legume production in Scotland?
- Technological
- Agronomic
- Economic
- Social
- Political
- Are you aware of any drivers or opportunities for legumes/protein sources in Scotland which either drive current production of may drive future production/supply?
    - Cultivation limitations,
    - What do you understand in terms of current legume production in Scotland?
- Are there any likely consequences, both positive and negative, from increased legume production?
- What do you think constrains increased production of legumes?

8.2.2 Details of organisations consulted

Table 12: Organisations consulted.

	Organisation
1	Graham Forbes, East Coast Vining
2	Peter Loggie, NFUS
3	Sheila George, WWF
4	David Michie, Soil Association
5	John Smith, Farming 1.5 enquiry panel member and farmer
6	Pete Ianetta and Ali Karley, James Hutton Institute - Legume Innovation Network
7	Robin Walker, SRUC- ReMIX
8	Chris Leslie, AHDB
9	Chris Bailey, RSPB
10	Nick Bradbury, Biomar Ltd
11	Peter Gorst, Carrs Billington Agriculture Ltd
12	Andrew Linscott, Alltech Crop Science
13	James McCulloch, Jane Salter, Agricultural Industries Confederation
14	John Murrie, Agro Vista UK Ltd
15	Paddy Jack, DLF seeds Ltd
16	James Wallace IAR Agri Ltd
17	Peter Scott, Origin Fertilisers

8.3 Appendix 3: PESTEL

Table 13: Summary PESTEL analysis: expansion of legume production in Scotland

	Opportunities	Constraints	Potential mitigation measures
Political	• Benefits multiple agriculture and environmental policy objectives relating to, GHG, water, air, soil • Contributes to priority catchments objectives • Reduce UK agriculture's reliance on imported soya for animal feed and aquaculture. More resilient against trade issues, supply issues and supports international action associated with potential ethical issues such as deforestation, soil degradation and biodiversity loss.. • Public health promotion of health benefits of increasing pulses in diet.	• Lack of clear specific policy objectives • Biomass energy policy incentivising alternative uses of productive land • World Trade Organisation rules do not allow environmental tariffs to be applied to reduce reliance on cheaper imported soya. • Changes to land use may impact on the productivity or profitability of land – conflicts between policy objectives.	• Future policy support for integrated climate, air and water and productivity policy. • Facilitation through advice services • Public education to enhance awareness of the food chain reliance on soya. • Historically policy mechanisms have successfully incentivised increases in legume production. Recent policies across Europe have successfully encouraged increased production.

Economic	• Productivity and yield improvements available over the long-term with crop developments, improving agronomy and more confidence/familiarity in growing legumes. • New markets developing for vegetable protein for human consumption providing higher value returns (e.g. protein flours). • Rise in vegetarianism and veganism provides an increasing UK market for pulses- currently most fava beans are grown for export e.g. to Egypt and Sudan for falafel flour. Other countries such as Canada (Pulse Canada) are already focused on developing a premium market for human consumption. • Pledges from big retail chains, e.g. Tesco, which has set a target of 300% increase in sales of plant-based meat alternatives by 2025 as part of plans to reduce the environmental impact of the average shopping basket.	• High variability in yield from, 3.2 -6 tonnes per ha gives farmers little security of income and processors a very variable supply. • Farmers taking a short-term view looking at the financial returns of the single crop rather than the benefits across rotations. • The small volumes produced in Scotland and highly variable yields do not give processors the certainty of supply needed to develop infrastructure but without this lack of infrastructure becomes a market barrier. • Arable legumes compete for land with higher value bioenergy crops, cereal crops and vegetable crops for human consumption. • Little market for homegrown proteins - tend to be home fed to livestock, premium market for human consumption can be difficult to access. • The UK consumer perceptions of pulses is poor except in coeliac, vegetarian and vegan diets, whereas they are considered a staple in other cultures. Consumption of pulses has consistently fallen of recent decades. • Financial support mechanisms for protein crops were available in Scotland in the	• Improved facilitation and advice for farmers on wider soil, biodiversity, production and rotational benefits. • Financial support to incentivise legume production. This will reduce farmers' financial risk of crop failure and ensure a greater supply to provide processors with certainty of supply • Support for food technology and innovation of new higher value products utilising protein crops e.g. Distilling, beer, protein flours, breakfast pulses, Japanese style pea-based flour snacks. • Establishing local markets through public procurement and promotion of the environmental benefits.

	• Pea protein consumption doubled globally between 2015 and 2020 with the rise in plant-based meat alternatives. • Opportunity to develop more local markets for pulses as local sourcing becomes more of a societal priority. • As nitrogen fertiliser costs rise, the economics of leguminous crops become more attractive. • Arable silage with a legume mix offers a more secure domestic market. • Potential supply reductions in alternative protein sources e.g. rapeseed meal, soya, distillery by-products could drive increased demand and improved prices for legumes.	1990s but as these were removed the cropping area reduced. • Vining pea (fresh peas/beans) require land to be free of any pea or bean crop for 6 years prior to establishment. These areas of land are already well established around the processing plants. Increases in combinable peas and beans in these areas could significantly impact upon this production.	
Social	• Meeting societal demands to reduce use of unsustainable soya. This will increase demand for other protein sources for feed. E.g. M&S announced that from 1st Oct 2020, they would have "completely eliminated soya from the production of all its milk'	• Experience of a failed crop results in businesses reluctant to engage with the process again particularly if changes to direct payments increase the vulnerability of businesses to financial risk. • Reports of other farmers having poor results with legumes results in risk aversion and a lack of willing to experiment.	• External facilitation to assist with knowledge sharing. • Demonstration events and farms – knowledge sharing and applied research to support improved practice on farm. • Engagement with the entire supply chain. Collaboration and partnerships should help to

	• Environmentally conscious farmers are increasingly interested in legumes, reduced inputs of inorganic fertiliser. • Techniques such as undersowing or slot seeding in grassland or as part of a more varied rotation of arable land can help improve environmental performance of farms. • Word of mouth and recommendation from farmers adopting legumes will influence others e.g. RSPB corn bunting work in Fife. Farmers used legumes in greening options, word of mouth led to others adopting to build the fertility of their land.	• The current push back on soya is yet to substantially put pressure down the supply chain to create a shift in the formulation of livestock rations • Businesses (e.g. pig production) have established supply chains utilizing soya and tend to resist change of the status quo unless rising prices force an exploration of other options	identify opportunities and remove barriers to support changes to practice.
Technological	• Development of new varieties with shorter maturation times to suit Scottish growing conditions. • Develop new varieties with higher protein content and larger seeded to replace soya. • Protein crops work well in a no tillage system.	• Knowledge gap in the agronomy of legumes both in farmers and advisers. • Less varieties suitable to Scottish conditions and lack of investment in plant breeding/selection for varieties with reduced maturation time to fit in the shorter growing season in Scotland. • Reduced pesticide availability of approved chemicals for weed control. Seed treatment and common desiccants	• Investment support for infrastructure development such as hulling, fractionation and milling facilities • Support for research/breeding programmes • Advice and guidance on crop establishment and plant protection products

	• Lentils, peas and beans are proven to establish well in Scotland. • Forage legumes can be grown on less optimal land i.e. Clover in the grass sward. • Expanding the use of legumes in cover crops and green manures offer a major opportunity with less risk than arable legumes. • New novel methods of utilising legumes offer opportunities for increase productivity e.g. intercropping, rotational benefits, whole crop silages.	(used to dry late ripening crops) such as Diquat are no longer available. • Poor understanding of soil micro/macro biology and how we influence that for the benefit of crop/environment. • Soil biodiscretionary technologies are already used in other countries – uptake in UK is slower. • Lack of knowledge of protein content available leads to poor rationing of arable silage/forage legumes and farmers not achieving the full economic return. • Lower levels of digestible protein available compared to soya is seen as a barrier to utilising in feeding ruminants. This is important for lamb and milk yield, but not so critical for the beef sector. • Livestock/mixed farms tend to have quite simple rotations. The more complex 1 in 6 rotation required for legumes is not so easily integrated. • Lupins and soya have not been found to thrive in Scotland and are easily outcompeted by weeds. • Lucerne needs liming and free draining soil but should grow in areas such as East Lothian and is used in organic dairying	• Ensure agriecological principleses are part of the curriculum for agricultural education • Innovative farmer networks to share experience and good practice • Advice on feed rationing to achieve best value from crops • Promoting liming of grassland would support clover establishment however liming itself has large GHG emissions associated with it. • Advice on strategies to utilise Intercropping to best advantage: examples stated: Intercropping provides resilience to crop failure and had been shown to increase the protein content of barley. • Whole crop silage provides a solution for the Scottish climate as this can be cut green and ensiled. • Undersowing with clover then provides a green cover to protect from soil erosion in winter. • Opportunities to intercrop legumes and cereal, killing off legumes once soil benefits have been

		• Clover is historically widely naturalised but cannot compete in soil below pH 5.5, grassland is not so widely limed as arable land. Even with liming there is evidence that in areas of high rainfall the benefit can be lost in a few years- resulting in a cut off of where it is financially beneficial to lime). • Clover does not grow until the soil temperature is 12-14 degrees centigrade • Poor drainage, compaction and pH are a significant restraint on the establishment of legumes- beans are particularly sensitive to this. • The wide rotation required for grain legumes (6 year rotation) restricts areas of arable land potentially limiting expansion.	accrued, thus allowing the cereal to be harvested as a single crop.
Environmental	• Improve soil structure, microbial health (impact on nutrient cycling) and resilience • Reduced artificial nitrogen inputs will benefit biodiversity, air and water • Improved habitat through reduced eutrophication nitrate deposition	• Climatic conditions limit the establishment of some legumes in Scotland. Trials of soya have failed to establish successful crops, even in varieties that have worked in Sweden and Germany. • The climatic trend towards wetter summers is difficult for these late harvesting crops, impacting quality of crop and access to land.	• Ensure legumes are included in NVZ and nutrient management plans • Ensure advice and guidance include potential limitations and restrictions of legumes.

	• Living manures - such as lucerne, clover providing biologically fixed nitrogen. • Soil health benefits – improved structure and nutrient status	• Potential for nitrate leaching if poorly managed sites.	
Legal/Regulatory	• Agri-environment scheme options and ecological focus areas promote the use of legumes, providing soil health and fertility, support pollinators, diffuse pollution benefits. • Legumes could form part of a strategy to reduce agriculture's carbon footprint. • Post-Brexit review of farm support could promote the use of legumes • Post Brexit changes in trade patterns could result in more market demand.	• Management of the crop is important to harness the full environmental benefits and not risk unintended consequences. E.g. Should there be a greater shift to forage silage production if it could negatively impact ground nesting birds such as skylarks and wading species. • World Trade Organisation rules do not allow countries to put in place barriers to influence demand for soya	• Advisory services must coral together information from a variety of sources to ensure advice is comprehensive and not single issue focused.

8.4 Appendix 4: Potential for sustainable expansion of legume crops

8.4.1 Review of crop constraints

A review of the suitability of land for legume crops production was completed. Legume crops that had the potential to be grown in Scotland were selected for analysis following a literature review, with crops defined as follows:

- forage legumes
    - white and red clover
    - common vetch
    - lupins
    - lucerne
- grain crops
    - peas
    - beans
    - faba beans
    - soya beans

Within the review the main constraints to growth of legumes were found to be rainfall and temperature. Access constraints, soil type and land use and availability also limit areas for growth (Table 14). Specific constraints of rainfall, temperature and altitude for each crop were assessed to attain the GIS ruleset parameters.

Table 14: Shortlist of constraints showing relevance to crop types

Constraint number	Short name	Description
Relevant to all legume crops		
1	Access constraints	Need for adequate access for planting and harvesting machinery. Machines are often large and can be restricted by risks to soil, access to the public road network, and slope. Difficult or slow access can increase costs by, for example, requiring the use of tracked vehicles.
2	Lack of agronomic advice	Lack of updated and unbiased technical advice and information for farmers and land owners; poor knowledge of management techniques.

Constraint number	Short name	Description
3	Land availability	Potential competition with other food and fodder production if grown on arable land; can be grown on permanent grassland, especially as a forage mix. Existing forest should be excluded. Should not be planted on land with a high conservation value (Land Use Consultants, 2007), including peat bogs. Should not be grown on land with designated area exclusions (National Park, National Scenic Areas, Open Access land, SSSI, SAC, SPA, Ramsar, non-statutory sites), or areas of historical significance.
4	Soil type	Exclude: high organic matter/peat, marine clay, shallow excessively stony/chalky soils. On peat/high organic matter soils, likely to be challenging to harvest as soil capability in terms of supporting heavy machinery is poor, leading to soil damage and erosion.
5	Soil carbon loss	Establishment on high organic/peaty soils potentially detrimental to soil carbon levels. Such soils in Scotland are found mainly in upland areas: for example, in north east Sutherland (the Flow Country) and in many areas across the Highlands and Islands.
6	Waterlogged soils	This crop cannot be planted on land with soils that are water-logged for most of the time, because the crop does not perform well under these conditions.
7	Steep slopes >15º	Land with steep slopes (any land with a slope greater than 15º) is not suitable (Tubby & Armstrong, 2002) because of machinery limitations.
8	Winter hardiness	Hard wintry conditions for long periods of time, frozen ground and early spring and early autumn frosts can halt growth, causing diminished achievable yield; in severe conditions plant loss can occur.
9	Climate	Lower overall day degrees in some parts of Scotland likely to cause reduced yields with current UK varieties.

The constraints in the shortlist can be reflected to some extent in a ruleset for quantifying the area of land that is agronomically suitable for legume crop growth. Some of the constraints can be used in an analysis of spatial data, such as climate, soil type and topography (gradient). Other constraints cannot be used in an analysis of the spatial data, such as lack of advice, limited availability of pesticides and machinery limitations; these do not influence the area of agronomically suitable land but will modify the extent and uptake of legume crop growth.

Table 15: Crop constraint parameters

Legume variety	Forage/grain	Annual Rainfall (mm)	Temperature (^oC)	Altitude (m)
Red clover	Forage	310-1290mm	Mean annual temperature 4.9-20.3 degrees Optimal at 18-25 degrees	N/A
White clover	Forage	N/A	Mean annual temperature 4.3-21.8 degrees	N/A
Common vetch	Forage	310-1630mm	N/A	N/A
Blue lupin	Forage	N/A	N/A	N/A
White lupin	Forage	400-1000mm through growing period	Tolerates frost, but optimal at 18-24 degrees	From sea level to 740m
Lucerne/Alfalfa	Forage	600-1200mm	Optimal at 25 degrees average, however winter hardly varieties	N/A
Faba bean	Grain	700-1000mm	Optimal at 18-27 degrees	Up to 2500m
Soya bean	Grain	Optimal at 500-850mm	Optimal at 30 degrees	Up to 2000m
Pea forage	Grain	Optimal at 800-1000mm	Optimal at 7-24 degrees	Up to 1000m
Common bean	Grain	Grow at to 300-3400mm, however optimal at 500-1500mm	Mean annual temperature 15-23 degrees	Up to 3000m

The main sources used in the review were:

- expertise of the project team based on industry experience
- Feedipedia encyclopaedia of animal feeds (2019)
- The practical effectiveness of nitrogen-fixing crops (Iannetta et al., 2019)
- Combinable protein crop production report (Wright, 2008)
- Legume Futures Report 1.3 (Stoddard, 2013)
- Legume Futures Report 1.6 (Reckling et al., 2014)
- Crop production in the East of Scotland (Hay, 2000)
- Effects of cold temperatures on winter annual legume cover crops (Thurston, 2019)
- Nitrogen fixing crops SRUC (Baddeley, 2020)

8.4.2 GIS analysis

Upper estimates of areas **theoretically** suitable for legume crop production were calculated using a simple exclusion-based approach within GIS (similar to Andersen et. al. (2005) and Lovett et. al. (2014). This approach was applied to the two crop types, forage crops (including red and white clover, common vetch, lupins and lucerne) and grain crops (including faba bean, soya bean, peas and beans). The excluded areas were deemed to be unsuitable on growing conditions and constraints based on expert judgement and the literature review. There was also a need to exclude land currently used for agriculture or forestry as well as any designated sites of scientific or cultural significance. In addition, land acknowledged as having biodiversity value and importance, such as designated sites, peat land etc. was excluded to further protect biodiversity. These excluded areas were used to create a series of rulesets which were used in the GIS to create the final land suitability layer for the two crop types. Data covering the entirety of Scotland, including all islands, were used. Details of the datasets and the rulesets are provided in Table 16.

8.4.3 Rulesets

The exclusion-based GIS approach used for the identification of suitable land for legume crop growth relies on a range of freely available datasets. Specific attributions to their use are required by these datasets. In order to fulfil this requirement, and acknowledge their use, a full list of data attributions is provided in Table .

For each of these datasets a series of assumptions based on the literature and expert judgement are used to determine what variables within these datasets should be used to exclude land area to ultimately derive suitable available land for legume crop growth. The rulesets are presented briefly in Table 15, but the detail behind the individual rulesets is presented in full in the data exclusions and assumptions section below. Following this, specific assumptions for datasets are presented along with detail on the processing of the topographic and climate datasets (these being data derived from processing of raster data rather than direct use of the other freely available vector datasets).

Datasets were processed within QGIS (QGIS Development Team, 2020), SAGA GIS (Conrad, et al., 2015) and GRASS GIS (GRASS GIS Development Team, 2020). The rulesets (Table 16) were applied in a step by step fashion to the datasets using geoprocessing difference calculations within QGIS and SAGA GIS.

This generated a separate dataset for each of the two crop types. The methodology applied is outlined below:

- **Step 1a –** Generate topographic exclusion datasets for elevation and slope angle based on the critical threshold parameters (Table 15) from a 50m digital elevation model of Scotland.
- **Step 1b –** Generate rainfall and temperature exclusion datasets based on the critical threshold parameters (Table 15) using the CEH GEAR and CHESS datasets.
- **Step 2a –** Remove excluded land classifications from Land Capability for Agriculture (LCA) layer. The output formed the *LCA base layer* from which all other exclusions are based.
- **Step 3a –** Remove the National Forestry Inventory Woodland areas from the LCA *base layer*.
- **Step 3b –** Remove peat bog land areas (using the Carbon and Peatland Map dataset) from the relevant *base layer* (output from Step 3a).

- **Step 4a –** Remove all landscape designation areas from the relevant *base layer* (output from Step 3b).
- **Step 4b –** Remove all cultural designation areas from the relevant *base layer* (output from Step 4a).
- **Step 4c –** Remove all scientific designation areas from the relevant *base layer* (output from Step 4b).
- **Step 5 –** Exclude the areas in the relevant *base layer* (output from Step 4c) which fall outside the topographic exclusion datasets created in Step 1a.
- **Step 6 –** Exclude the areas in relevant *base layer* (output from Step 5) which fall outside the rainfall and temperature created in Step 1b.
- **Step 7 –** Calculate the area of the remaining land (using the output from Step 6) to calculate the suitable land available for growing the two legume crop types.

Table 16: Detailed dataset and rulesets table

Ruleset	Datasets	Exclusion criteria	
		Forage leguminous crops	**Grain leguminous crops**
Land capability - agriculture	James Hutton Institute: Land Capability for Agriculture, 1:250,000	Land Capability classes removed: • 6.1 • 6.2 • 6.3 • 7 Additional non-agricultural land classes removed include: • 888 (Built up areas). • 999 (Inland water). • 9500 (Unencoded islands).	Land Capability classes removed: • 5.1 • 5.2 • 5.3 • 6.1 • 6.2 • 6.3 • 7 Additional non-agricultural land classes removed include: • 888 (Built up areas). • 999 (Inland water). • 9500 (Unencoded islands)
Elevation	Ordnance Survey: Terrain 50 (50m cell resolution DEM).	Over 750m	Over 750m
Slope angle	Ordnance Survey: Terrain 50 (50m cell resolution DEM).	Slope >15°	Slope >15°
Rainfall	Centre for Ecology and Hydrology: Gridded Estimates of Areal Rainfall (GEAR) (1km cell resolution).	>1000mm annual average	>850mm annual average
Temperature	Centre for Ecology and Hydrology: Climate Hydrology and Ecology research Support System (CHESS) (1km cell resolution).	<10 - >25°C average summer temperature	<10 - >25°C average summer temperature

<table>
<tr><th rowspan="2">Ruleset</th><th rowspan="2">Datasets</th><th colspan="2">Exclusion criteria</th></tr>
<tr><th>Forage leguminous crops</th><th>Grain leguminous crops</th></tr>
<tr><td>Soil type</td><td>James Hutton Institute: National Soils of Scotland, 1:250,000</td><td colspan="2">Exclusion dataset created by selecting the following soils from the dataset (selected using SERCDE1 attribute field and code):
• Bare rock (SERCDE1 code 99998).
• Basin peat (SERCDE1 codes 60610 and 6061092).
• Blanket peat (SERCDE1 codes 60660, 6066098, 60662, 6066292 and 6066092).
• Saline alluvial soils (SERCDE1 code 72499).
• Saline gleys (SERCDE1 code 08706 and 76906).
• Scree (SERCDE1 code 99997).
All other categories were removed.</td></tr>
<tr><td>Peat land</td><td>Scottish Natural Heritage: Carbon and Peatland Map 2016</td><td colspan="2">Exclusion dataset created by selecting the following peat classes from the dataset (using PRIMARY_LA attribute field from the dataset):
• Blanket bog/peat veg.
• Industrial peat.
• Other peat.
• Wetlands.
All other categories were removed.</td></tr>
<tr><td>Forestry</td><td>Forestry Commission: National Forestry Inventory Woodland Scotland 2017 (areas of 0.5ha and greater)</td><td colspan="2">Exclusion dataset created by selecting the following forestry classes from the dataset (using the IFT_IOA attribute field from the dataset):
• Broadleaved.
• Conifer.
• Coppice.
• Coppice with standards.
• Mixed mainly broadleaved.
• Mixed mainly conifer.
• Young trees.</td></tr>
</table>

<table>
<tr><th rowspan="2">Ruleset</th><th rowspan="2">Datasets</th><th colspan="2">Exclusion criteria</th></tr>
<tr><th>Forage leguminous crops</th><th>Grain leguminous crops</th></tr>
<tr><td></td><td></td><td colspan="2">Specific classes removed due to ambiguity or not representing suitable land include:
• Non woodland.
• Ground prep.
• Assumed woodland.
• Felled.
• Cloud \ shadow.
• Failed.
• Uncertain.
• Low density (includes areas which could have opportunity for tree planting).
• Shrub (uncertain, but possibly may grow into trees in the future).
• Windblow (areas of trees uprooted by the wind but not removed).
Non-woodland was identified in the dataset Category attribute field. All others were identified in the IFT_IOA attribute field.</td></tr>
<tr><td>Waterbodies</td><td>Ordnance Survey: Open Zoomstack</td><td colspan="2">Features to exclude from land suitability:
• Rivers
• Lakes
All other features were removed.</td></tr>
<tr><td>Landscape designations</td><td>Scottish Natural Heritage: multiple datasets</td><td colspan="2">Designated areas to exclude from land suitability:
• Cairngorms National Park.
• Loch Lomond and the Trossachs National Park.
• Country Parks.
• National Scenic Areas.
• Council of Europe diploma sites.</td></tr>
<tr><td>Cultural designations</td><td>Scottish Natural Heritage: multiple datasets</td><td colspan="2">Designated areas to exclude from land suitability:
• Battlefields.</td></tr>
</table>

Ruleset	Datasets	Exclusion criteria	
		Forage leguminous crops	Grain leguminous crops
		• Conservation areas. • Gardens and designated landscapes. • Historic Marine Protected Areas. • Listed buildings. • Scheduled Monuments. • World Heritage Sites.	
Scientific designations	Scottish Natural Heritage: multiple datasets	Designated areas to exclude from land suitability: • Ancient woodland. • Biogenetic Reserve. • Biosphere Reserve. • Geological Conservation Review sites • Local Nature Reserves. • National Nature Reserves. • Nature Reserves. • Ramsar. • SAC. • SPA. • SSSI.	

8.4.4 Data exclusions and assumptions

Notes on the reasons for excluding data and the assumptions applied to datasets are provided below on a per dataset basis.

Land capability – agriculture

The Land Capability for Agriculture layer forms the base layer for the land suitability assessment as it contains all land within Scotland classified for its suitability for growing agricultural crops. For the assessment the Land Capability for Agriculture dataset was considered for both forage and grain legumes.

Summary descriptions of all Land Capability for Agriculture classes are presented in Table in order to help understand the differences between each land use class. These are summary descriptions only since each of the actual descriptions are verbose and detailed. The full original descriptions can be found in Bibby et al. (1991)[3] with useful summaries and visual information presented in *Land Capability for Agriculture in Scotland*[4].

As the remit of the project is to identify opportunities for potential expansion of legume crops it was critical to include prime agricultural land capable of supporting arable and mixed agriculture for both forage and grain legume crops and improved grassland categories for forage crops. Rough grazing classes (highlighted in light grey in Table) were removed from the dataset.

[3] Bibby, J.S., Douglas, H.A., Thomasson, A.J., and Robertson, J.S. (1991). Land Capability Classification for Agriculture. Macaulay Land Use Research Institute, Aberdeen. 84pp.
[4] https://www.hutton.ac.uk/sites/default/files/files/soils/lca_leaflet_hutton.pdf (accessed 28 October 2019).

Table 17: Land Capability for Agriculture class descriptions

Land Capability for Agriculture class ID	Summary class description
1	Very wide range of crops.
2	Wide range of crops.
3.1	Moderate range of crops - high yield (cereals and grass), moderate yield (potatoes, field beans, root crops).
3.2	Moderate range of crops - average production. High yields barley, oats and grass.
4.1	Narrow range of crops - suited to rotations.
4.2	Narrow range of crops - primarily grassland, limited potential other crops.
5.1	Improved grassland - grass sward.
5.2	Improved grassland - grass sward, moderate to low trafficability issues.
5.3	Improved grassland - grass sward, serious trafficability issues.
6.1	Rough grazing - high proportions of palatable herbage.
6.2	Rough grazing - moderate quality of palatable herbage.
6.3	Rough grazing - low grazing values.
7	Very limited agricultural value.

The remaining land capability classes (1 - 5.3 for forage crops and 1 – 4.2 for grain crops) were used in the dataset for subsequent exclusion of all other datasets listed in Table 16.

Elevation

The OS Terrain 50 DEM is the most current dataset which covers the entirety of Scotland and provides a representative view of the elevation of the Scottish landscape.

The use of elevation is an approximation to the combination of a range of more complex variables such as exposure, continentality etc. which is beyond the scope of this study. However, it is taken that elevation provides a good surrogate in this regard to understand limits on crop yield and hence land suitability. An upper limit of 750 m was selected to reflect land accessibility for forage and legume crops and altitude limit of white lupins (Table 15).

Slope angle

This is a dataset which is derived from geoprocessing of the OS Terrain 50 DEM. Further details on the geoprocessing of the dataset is provided below. The selection of critical slope angles for the crop types were provided from guidance by the project team. Land steeper than 15° slope angle should be excluded as it is not currently physically possible to plant and establish these crops on such steep land.

Rainfall and temperature

Rainfall and temperature thresholds are used to exclude land based on climatic factors. These are generated from 1km resolution datasets of rainfall and air temperature. The data is taken as an average air temperature and average rainfall between 1981 and 2000 (CEH CHESS), in line with data assessed for the latest UK Climate Projections. The use of a 1982-2000 average provides a smoothed value over the last ten years against which to exclude land use against climate. Climate values have been derived from crop constraints found in relevant literature. Leguminous crops were found to have a wide temperature range with poor crop growth cause by drought or frosts, however optimal growth was seen between 10-25°C for most legume varieties.

It should be noted that the CEH-CHESS dataset does not cover Shetland (although the CEH-GEAR dataset does). Analysis of the dataset indicates that the temperature range does not exceed the optimal range (<10 to >25°C) outside of the highest elevation areas of the Scottish Highlands or the islands (including Orkney). Therefore, non-coverage of Shetland by the temperature dataset can be concluded to not be an issue for the analysis.

Soil type

The soil type data was selected as it provided a complete coverage over the entirely of Scotland. Although a higher resolution and more up to data product available (25,000 scale soil type dataset available from the James Hutton Institute) this only offered partial coverage of the country, covering productive agriculture areas of the country only. Also, it was not possible to simply merge the 250,000 scale dataset with the 25,000 scale dataset as they were digitised differently. Additionally, the 250,000 scale dataset accorded with the scale of the Land Capability for Agriculture dataset. Therefore, the choice to use the 250,000 scale soil layer in this project was taken.

It was agreed to exclude soil types which had high organic matter contents (peat), soils which were excessively shallow or stony and those which had a marine or estuarine influence (saline) as these were deemed unsuitable for agricultural purposes. These exclusions applied to both crop types considered.

Peat land

Although peat land soils were excluded from the soils layer, it was concluded that a specific peat land layer should be used to exclude those areas which had been mapped as peat bogs in order to protect this extremely important land and habitat. As such the dataset selected was deemed to afford the best spatial coverage of peat land throughout Scotland and therefore would remove nearly all peat land from the land suitability estimates. However, not all datasets are accurate and obviously at the time of implementation of legume crop production specific steps should be made at a site level to prevent planting and destruction of peat land areas.

Forestry

Land currently used for forestry (regardless of the type of species planted) was excluded from the dataset to prevent these from being included as suitable land for legume crop planting. The National Forestry Inventory Woodland was selected as the most current dataset (2017) which accurately represents woodland in Scotland (and the Great Britain) over 0.5 hectares in size and is updated on a five-year period[5].

As noted in Table 16 a certain number of forestry type categories within the dataset were excluded (namely *low density*, *shrub* and *windblow*). Although the National Forestry Inventory metadata indicated these areas of land could possibly be covered in trees, they are also areas which have opportunity for tree planting (*low density*), are uncertain if trees are present (*shrub*) and areas of trees which have been uprooted but not removed (*windblow*).

Waterbodies

Waterbodies were excluded using the OS Open Zoomstack water layer. As the Open Zoomstack dataset is designed to have different visibility of features at different topographic

[5] https://www.forestresearch.gov.uk/tools-and-resources/national-forest-inventory/about-the-nfi/ (accessed 10 October 2020).

scales only those rivers and lakes categorised as "*local*", i.e. the highest resolution data visible at the largest scales, were used. The "*regional*" and "*national*" features (essentially lower resolution version of the more detailed "*local*" features) were excluded. The *local* feature waterbodies include lakes down to around 40m^2 in area and rivers around 6 m in width. Other much smaller lakes and rivers, such as tributaries and drains, were not excluded as these were deemed to be below the overall spatial resolution of the datasets used.

Landscape designations, cultural designations and scientific designations

It is key that any future legume crops are not grown on currently protected areas, where these are landscape, cultural or scientific designations, in order to maintain the integrity of these sites and to protect biodiversity (where necessary). For this reason the boundaries of a range of currently established designations (Table 16) were used to exclude these areas from being considered in the available suitable land.

Any purely marine designation boundaries were excluded. However, there are some designations which are marine but have boundaries which extend on the land surface (for example some Ramsar, SAC, SSSI and Historic Marine Areas).

For World Heritage Sites generally a specific site boundary existed. However, for three sites, the Antonine Wall, Heart of Neolithic Orkney and New Lanark, these had additional boundaries which extended beyond the World Heritage Site boundary. For these three sites the more extensive buffer zone was chosen for the exclusion boundary.

It should be noted that these are for current designations and consideration should be given to any new designations which may occur in the future during any site-specific planting schemes.

8.4.5 Processing topographic and climatic datasets

All datasets, except for the OS Terrain 50, rainfall and temperature datasets, were vector polygon datasets, i.e. shapes defined by specific vertices defined by a cartesian coordinate system which were joined between the two closest vertices by lines called segments. Vector data were the most appropriate way to perform the geoprocessing methodology.

The OS Terrain 50 dataset was raster data, i.e. graphical data where each cell is defined as a pixel of specific size, for example 50 m for the dataset. This dataset was processed slightly differently than the vector datasets. A brief outline of the processing steps used each of these datasets is presented below.

- **OS Terrain 50 –** In its unprocessed state, this dataset is representative of surface elevation (in metres above ordnance datum (mAOD)) and this required no processing. The slope angle dataset was derived directly from this elevation by geoprocessing using the *Slope* algorithm within QGIS. For the resulting per crop type elevation and slope angle datasets these were merged into a single raster to create a Boolean exclusion raster (e.g. 0 representing areas not to be excluded and 1 representing areas which were to be excluded). The Boolean exclusion raster was converted to a vector using the QGIS *Polygonize* function.
- **Temperature and rainfall –** The raw raster data was provided as a series of NetCDF files. These were processed into the required ranges using a Geospatial Data Abstraction Library (GDAL)[6] script. The resulting output was converted to a vector using the QGIS *Polygonize* function.

[6] https://gdal.org/ (accessed 28 October 2019).

8.4.6 Uncertainty on areas of land suitability

High accuracy is not the aim of the current approach as broad values for guidance are required. It is acknowledged that the approach has used a certain number of datasets of differing spatial scales and collection periods. However, these data are considered to represent the best available data at the time of analysis and also the most appropriate data scales for the analysis undertaken. As with all analyses the application of an error provides some level of understanding of the uncertainty in the results and a value against which conclusions reached by, and from, the data can be placed into perspective.

The major sources of error are:

- Inaccurate representation of land cover types or features.
- Inaccurate representation of the boundary of land cover types or features.
- Spatial scales not capturing land cover types or features accurately.

8.4.7 Data attributions

The data used in the analysis was downloaded from multiple sources. In order to comply with their licences, as well as to acknowledge the use of the data, attributions for each data source is provided in Table . In all cases these attributions are those directly required by the data licence or metadata.

Table 18: Data attributions

Dataset name and data source	Data attribution
James Hutton Institute: Land Capability for Agriculture, 1:250,000 – http://nar.hutton.ac.uk/dataset/land-capability-maps	James Hutton Institute: Land Capability for Agriculture, 1:250,000 copyright and database right The James Hutton Institute 1980. Used with permission of The James Hutton Institute. All rights reserved. Any public sector information contained in these data is licensed under the Open Government Licence v.2.0
Ordnance Survey: Terrain 50 50m resolution digital elevation model (DEM) – https://www.ordnancesurvey.co.uk/opendatadownload/products.html	Contains OS data © Crown Copyright [and database right] (2019).
Ecological Site Classification	Forestry Commission, (2019).
Centre for Ecology and Hydrology (CEH): Gridded Estimates of Areal Rainfall (GEAR) – https://doi.org/10.5285/ee9ab43d-a4fe-4e73-afd5-cd4fc4c82556	Tanguy, M.; Dixon, H.; Prosdocimi, I.; Morris, D.G.; Keller, V.D.J. (2019). Gridded estimates of daily and monthly areal rainfall for the United Kingdom (1890-2017) [CEH-GEAR]. NERC Environmental Information Data Centre. https://doi.org/10.5285/ee9ab43d-a4fe-4e73-afd5-cd4fc4c82556
CEH: Climate Hydrology and Ecology research Support System (CHESS) – https://doi.org/10.5285/b745e7b1-626c-4ccc-ac27-56582e77b900	Robinson, E.L.; Blyth, E.; Clark, D.B.; Comyn-Platt, E.; Finch, J.; Rudd, A.C. (2017). Climate

Dataset name and data source	Data attribution
	hydrology and ecology research support system meteorology dataset for Great Britain (1961-2015) [CHESS-met] v1.2. NERC Environmental Information Data Centre. https://doi.org/10.5285/b745e7b1-626c-4ccc-ac27-56582e77b900
James Hutton Institute: National Soils of Scotland, 1:250,000 – http://nar.hutton.ac.uk/dataset/national-soils-of-scotland	James Hutton Institute: National Soils of Scotland, 1:250,000 copyright and database right The James Hutton Institute 2019. Used with permission of The James Hutton Institute. All rights reserved. Any public sector information contained in these data is licensed under the Open Government Licence v.2.0
Scottish Natural Heritage: Carbon and Peatland Map 2016 – https://gateway.snh.gov.uk/natural-spaces/	Contains public sector information licensed under the Open Government Licence v3.0.
Forestry Commission: National Forestry Inventory Woodland Scotland 2017 – http://data-forestry.opendata.arcgis.com	Contains Forestry Commission information licensed under the Open Government License v3.0.
Ordnance Survey: Open Zoomstack – https://www.ordnancesurvey.co.uk/opendatadownload/products.html	Contains OS data © Crown Copyright [and database right] (2019).
Scottish Natural Heritage: National Parks, National Scenic Areas, Country Parks etc. – https://gateway.snh.gov.uk/natural-spaces/	Contains public sector information licensed under the Open Government Licence v3.0.
Scottish Natural Heritage: World Heritage Sites, Battlefields, Conservation Areas etc. – https://gateway.snh.gov.uk/natural-spaces/	Contains public sector information licensed under the Open Government Licence v3.0.
Scottish Natural Heritage: Ramsar, SAC, SPA, SSSI etc. – https://gateway.snh.gov.uk/natural-spaces/	Contains public sector information licensed under the Open Government Licence v3.0.

8.4.8 Results

The resulting suitable land areas for forage and grain legumes based on the application of the exclusion methodology are presented in Section 8.4.2. Maps for the two crop types visually displaying the spatial distribution of available suitable land over the whole of Scotland are presented for reference below (Figure 4: and Figure 5).

Figure 4: Distribution of suitable land available for grain legume crops

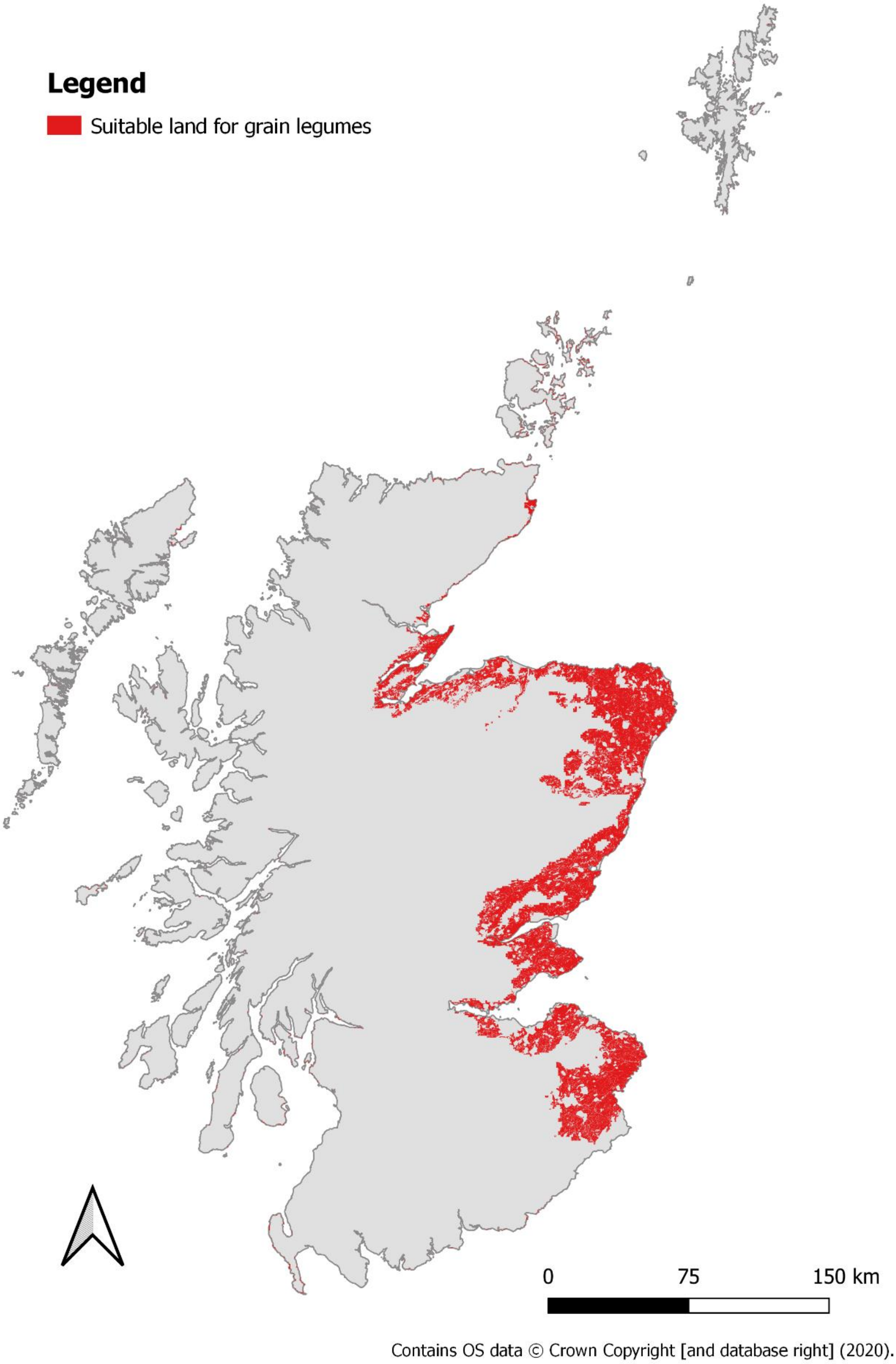
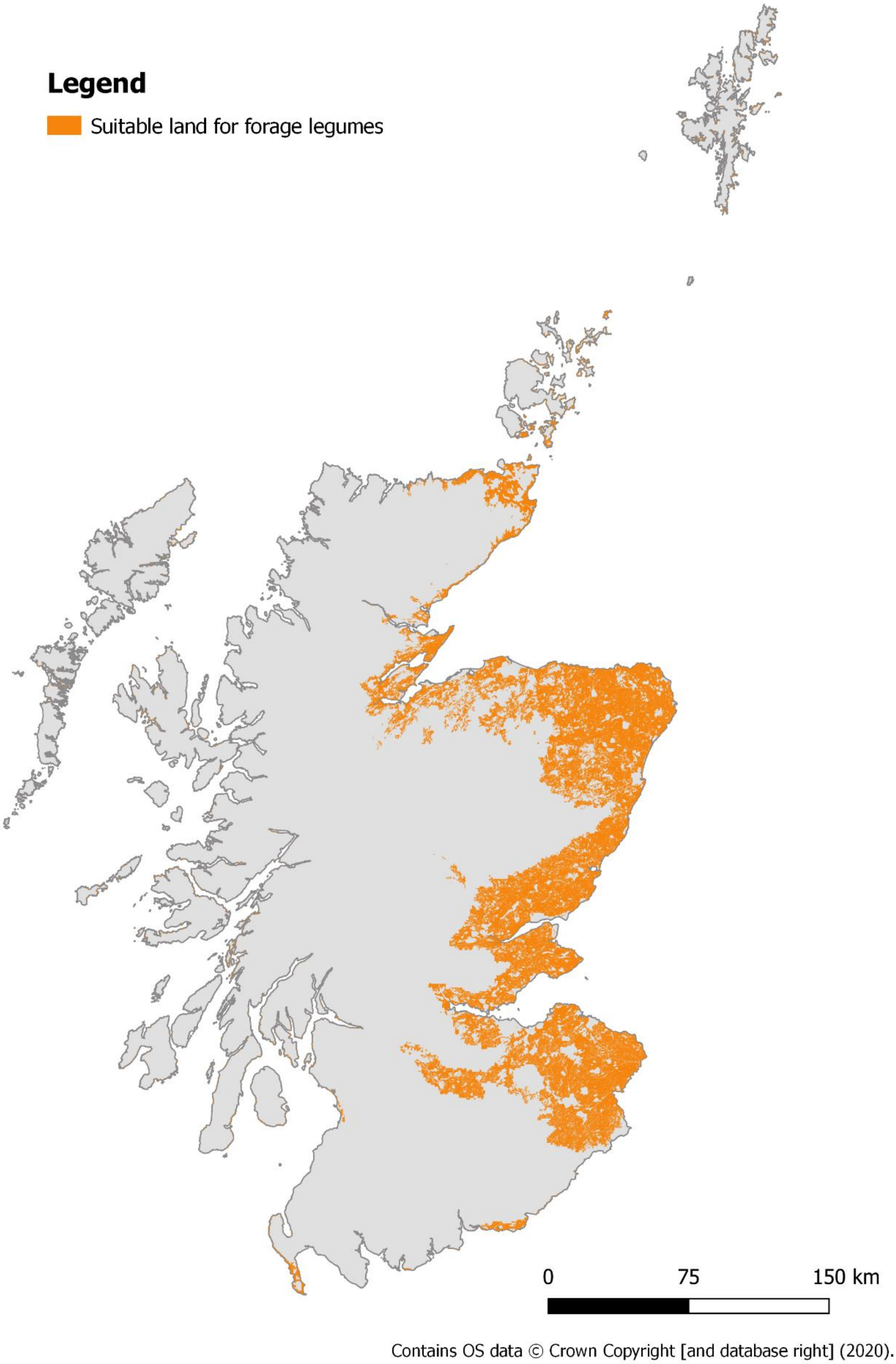


Figure 5: Distribution of suitable land available for forage legume crops



8.5 Appendix 5: Impact of changing climate on legume crops

A requirement of the study is to understand the change in available suitable land for growing legumes in response to future predicted climate change out to 2100. It should be noted that two key dates within Scottish climate change policy fall within this date range, namely the target for a 70% reduction in greenhouse gases in 2030 and the target for net-zero emissions in 2045.

For the purposes of this assessment, the most current predictions contained within UKCP18 were used. The areas of land suitability outputs from the analysis of opportunities and constraints for legumes in Scotland, prior to excluding the climatic threshold (rainfall and temperature) from the data, forms the basis of the calculations for predicting change in land suitability in response to climate change.

The following discusses the climate change scenarios used in the approach and outlines the methodology used to calculate the change in suitable land with climate change.

8.5.1 Overview of the UKCP18

As noted above, the climate change predictions used in this study are taken from the UKCP18 report (Lowe et al., 2018). The UKCP18 report provides projections of changes in a range of climate variables (including rainfall and temperature) for several time periods, namely eight, 19-year periods starting at 2010 and ending in 2099 referenced from a baseline period of 1981-2000. The UKCP18 approach uses the results of numerical modelling using climate models to provide probabilistic estimates of these climate changes for different greenhouse gas emissions scenarios. The outputs are an update of those presented in UKCP09 however the modelling uses new emissions scenarios than the UKCP09 work, these now being categorised as Representative Concentration Pathways (RCPs), which represent climate change against a range of socio-economic outcomes and which were used in the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment report (AR5) (IPCC, 2014). The RCP scenarios used in UKCP18 are RCP2.6, RCP4.5, RCP6.0 and RCP8.5. Each of the values are targets which represent the effects of increasing concentrations of greenhouse gases on radiative forcing (the difference between incoming and outgoing radiation at the top of the atmosphere), out to 2100, with each value being measured in W/m^2 (watts per square metre) (UKCP18, 2018).

For each of the RCP scenarios the predicted average change in surface temperature by 2081-2100 per RCP is 1.6°C (RCP2.6), 2.4°C (RCP4.5), 2.8°C (RCP6.0) and 4.3°C (RCP4.5). RCP2.6 is not equivalent to any emissions scenario used in UKCP09, while RCP4.5 is equivalent to UKCP09 low emissions scenario, RCP6.0 is lies between the low and medium emissions scenarios in UKCP09 and RCP8.5 is equivalent to the UKCP09 high emissions scenario (UKCP18, 2018). For each scenario, climate predictions are provided as probabilistic values of 5%, 10%, 50%, 90% and 95% predictions, for example a 10% probability is very likely to occur and a 90% probability is very unlikely to occur. These probabilistic projections account for uncertainties from modelling natural climate processes and variability in the climate system. No model can ever be completely correct, however the results of the UKCP18 climate predictions are considered to be sufficiently accurate as to give confidence that future predictions are plausible.

The forward climate predictions are provided for a range of administrative regions, with Scotland divided into three, East Scotland, North Scotland and West Scotland. These predictions indicate that under 50% probability (i.e. most likely to happen) under a RCP6.0 emissions scenario, Scotland is likely to have significantly warmer summers (2.6-3.2°C increase) and warmer winters (2.3 – 2.4°C increase) and drier summers (-15 to -22% decrease) and wetter winters (13-22% increase).

As noted above, a full appreciation of the UKCP18 approach and findings can be found in Lowe et al. (2018).

8.5.2 Selected climate change scenarios

Given that there are UKCP18 climate predictions for three different areas of Scotland we have chosen the East Scotland region as being most representative. This is because most of the land suitable for growing legume crops is located on the eastern margins of the country.

As noted above there are four climate prediction scenarios, each with their own range of probabilities. For the purposes of this project we have selected an RCP6.0 emissions scenario with a 50% probability. This selection was based on the fact that a medium emissions scenario is the most likely to be realised (given current global efforts to curtail emissions) and the 50% probability being the most likely climate change outcome. As there are eight individual time periods for the predictions we have selected three periods in order to give a good temporal coverage in changes out to 2100, specifically 2040-2059, 2060-2079 and 2080-2099.

The climatic thresholds of the legumes are defined in Table 16. For temperature thresholds the mean summer temperature is used, however for rainfall the thresholds are given as annual totals. As the UKCP18 results do not provide predictions for this data for the purposes of this study we have taken the mean percentage change of the UKCP18 predicted summer and winter season[7] changes in rainfall and applied this to the baseline climate dataset to create the future predicted change in annual total rainfall.

In summary our assumptions are:

- RCP6.0 emissions scenario at 50% probability.
- Climate predictions are used for East Scotland.
- Selected a narrower range of time periods for climate predictions.
- Use mean summer temperature and annual total rainfall changes.

Table 19 illustrates the raw UKCP18 forward predictions for mean summer rainfall and temperature for East Scotland (Lowe et. al. (2018)) with the calculated average of the summer and winter precipitation change used to calculate the change in annual total precipitation for the model highlighted in blue in the table.

Table 19: UKCP18 predictions for changing mean summer temperature and mean summer and winter rainfall for East Scotland for an RCP6.0 emissions scenario at 50% probability

	Time period of scenario		
Climate variable	**2040-2059**	**2060-2079**	**2080-2099**
Mean summer temperature (°C)	1.1	1.8	3.0
Mean summer precipitation change (%)	-7	-13	-22
Mean winter precipitation change (%)	10	10	15
Average of mean summer and winter precipitation changes (%)	1.5	-1.5	-3.5

[7] The UKCP18 defines the seasons as: winter (December, January and February), spring (March, April and May), summer (June, July and August) and autumn (September, October and November).

For the purposes of the climate modelling approach, we have created a 1981-2000 baseline dataset for temperature and rainfall in accordance with the baseline time horizon used in the UKCP18 predictions (Lowe et al. 2018) from which to calculate the change in mean summer temperature and mean summer precipitation at the three selected time periods (2040-2059, 2060-2079 and 2080-2099).

The methodology for applying the climate change scenario predictions to create mean summer temperature and total annual rainfall data for 2040-2059, 2060-2079 and 2080-2099 for legumes are presented below.

It should be noted that the CEH-CHESS dataset does not cover Shetland (although the CEH-GEAR dataset does). Analysis of long term data from the Met Office meteorological station in Lerwick[8] shows that over the baseline period 1981-2000 the average monthly temperature in the Summer (in either June, July or August) was around 10°C, with only 13 months (all in June) being below 10°C by, on average, 0.5°C. While this is slightly below the critical temperature threshold for legumes, this is likely to have only occurred over narrow temporal periods (with maximum temperatures during these months when the average was below 10°C generally being around 11-12°C). Thus, while there is a potential impact on predicting some areas of legume production in Shetland, the spatial scales being used in the assessment and the likely narrow temporal period when temperatures drop below 10°C suggest that this potential impact is very limited and will not impact on the predicted areas of land suitability for legumes. Therefore, it can be concluded that the non-coverage of Shetland by the temperature dataset is not an issue for the analysis.

8.5.3 Methodology

The methodology utilised two key climatic datasets, notably the Centre for Ecology and Hydrology's (CEH) Climate, Hydrological and Ecological Research Support System (CHESS) daily temperature data from 1981-2000 (as daily average temperature in Kelvin) and their Gridded Estimates of Areal Rainfall (GEAR) daily rainfall data from 1981-2000 (in daily total rainfall in millimetres) (Table). Both data were downloaded from the CEH website as NetCDF data which held daily UK temperature, covering each year for the GEAR data and each month for the CHESS data, as 1km resolution gridded datasets. Each day of the dataset was held as an individual daily raster array within the associated NetCDF file.

As the UKCP18 climate change predictions are based on seasonal changes, the daily data had to be converted to seasonal average data. As stated above, this project has assumed that the climate predictions will be based around the summer season for temperature and annual total average rainfall. Using a series of custom GDAL[9] scripts, the 1981-2000 rainfall and temperature data were converted into seasonal averages over the required periods. The temperature data were converted to degrees Celsius from Kelvin and the resulting temperature and rainfall outputs were clipped to Scotland. Using the resulting output datasets the predicted change in rainfall and temperature for the three periods selected (2040-2059, 2060-2079 and 2080-2099) were applied to the resulting datasets using a GDAL script to generate the required climate threshold datasets.

For the 2040-2059, 2060-2079 and 2080-2099 datasets for the legumes the appropriate rainfall and temperature threshold was used to generate a masked Boolean raster dataset which was then converted to a polygon using the QGIS *Polygonize* function. The resulting datasets were then excluded from the land suitability areas created in Step 6 (Section 8.5.3) in order to generate land suitability areas for the legumes in the three periods 2040-2059, 2060-2079 and 2080-2099.

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[8] Met Office, Historic station data, Lerwick, https://www.metoffice.gov.uk/pub/data/weather/uk/climate/stationdata/lerwickdata.txt. Accessed 19 October 2020.

[9] GDAL – Geospatial Data Abstraction Library. *http://www.gdal.org/*.

8.5.4 Results

The resulting change in suitable land areas for forage and grain legume crops with climate change are presented in Section 4.2.3. Maps for each of the crop types visually display the spatial distribution of available suitable land over the whole of Scotland for the baseline and climate projection periods (2040-2059, 2060-2079, 2080-2099). These maps are presented for reference below (Figure 6 and Figure 7).

As noted above, even with the climate change temperature increases these make no difference to the critical ranges for the crops because all of the changes in land suitability due to climate change are related to reductions in rainfall.

Figure 6: Distribution of suitable land available for grain legume crops with respect to climate change in 2040-2059, 2060-2079 and 2080-2099

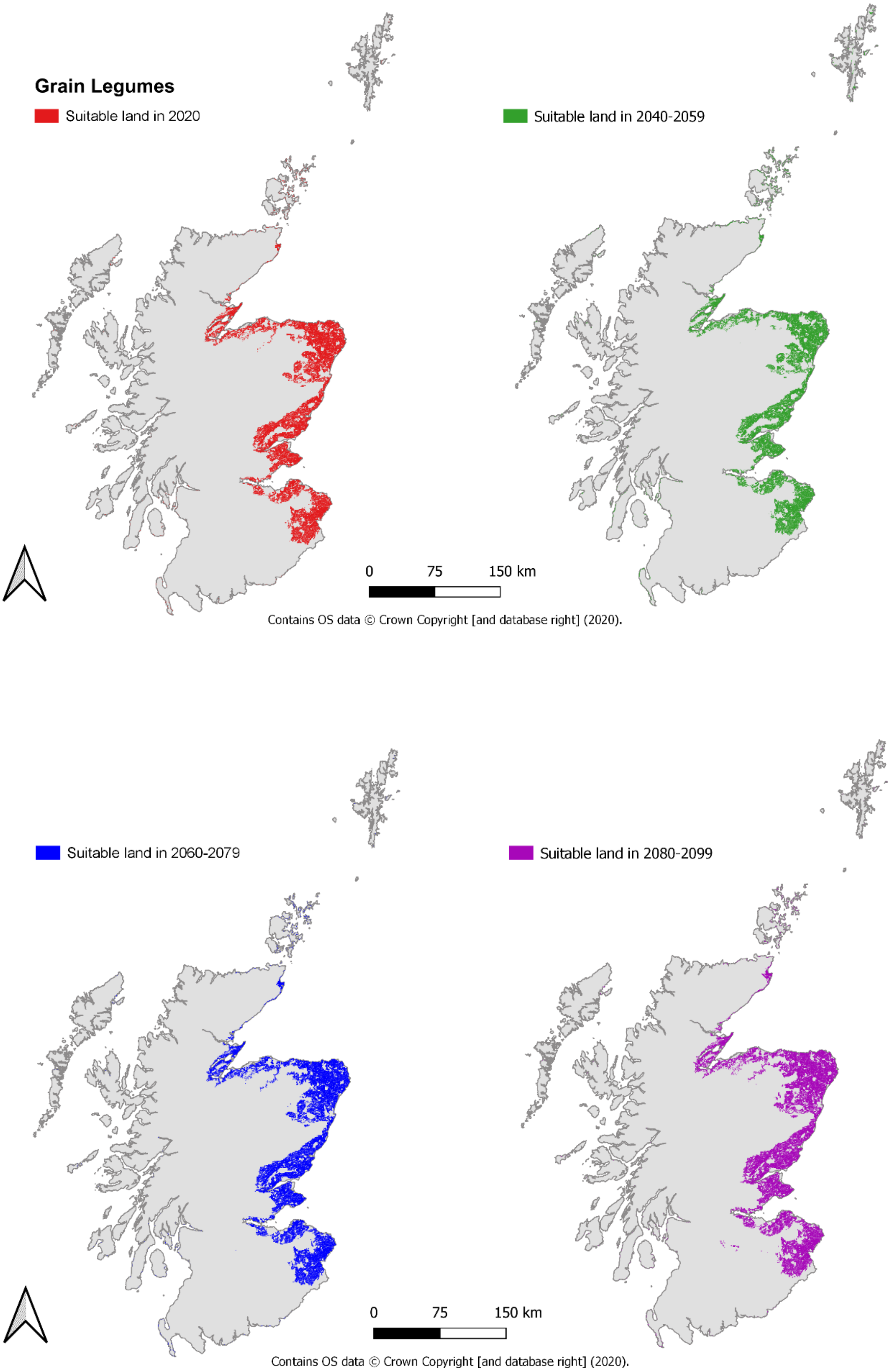
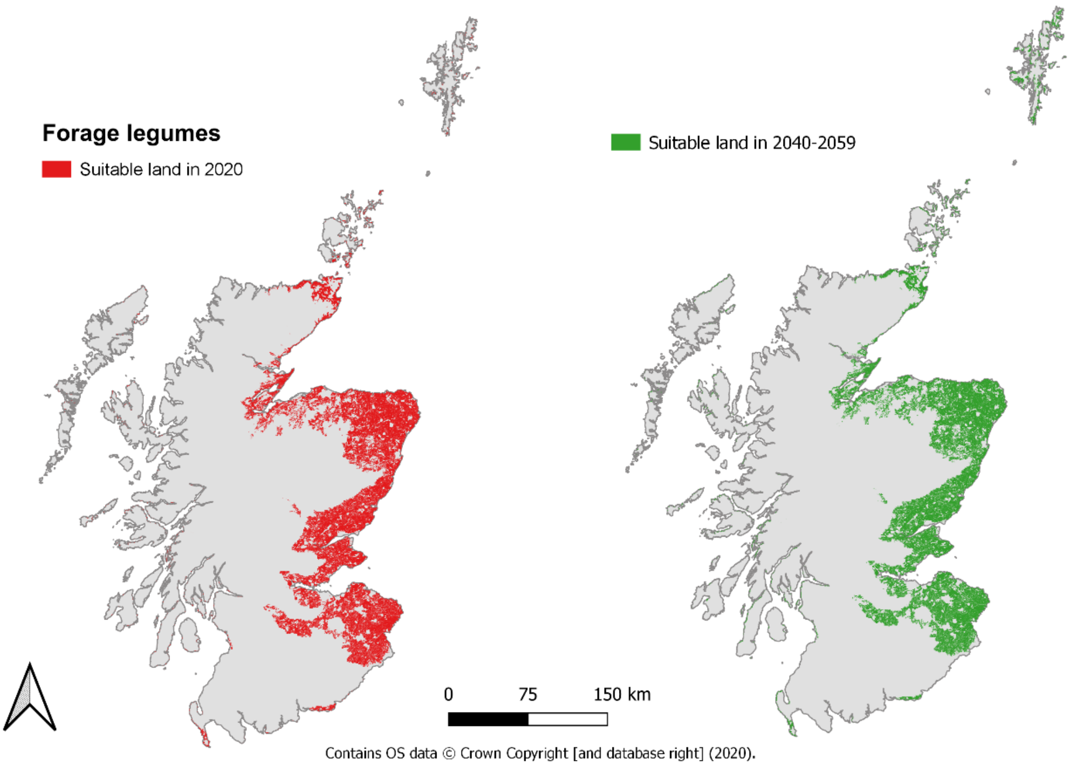
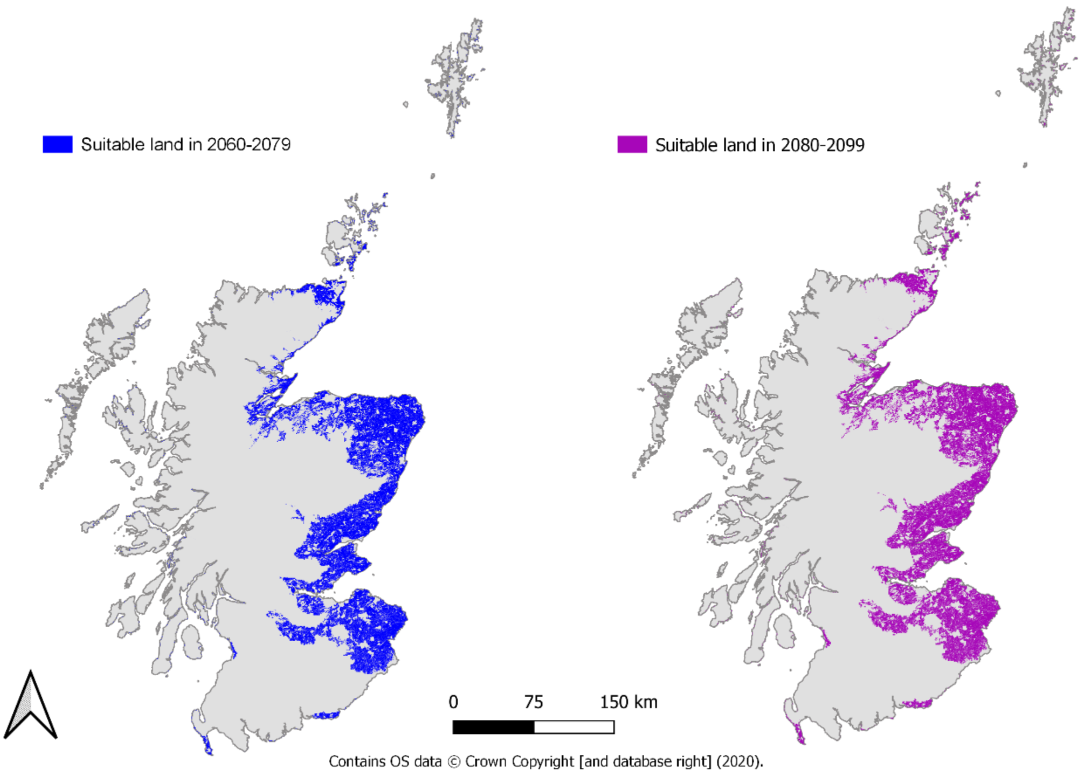


Figure 7: Distribution of suitable land available for forage legume crops with respect to climate change in 2040-2059, 2060-2079 and 2080-2099





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