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The Practical Effectiveness of Nitrogen-Fixing Crops: Policy Briefing

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Summary

In the 2018 Climate Change Plan, the Scottish Government committed to a reduction in emissions from the use of synthetic nitrogen fertiliser, which currently accounts for around 25% of the GHG emissions from agricultural soils[1]. One approach is to increase cultivation of nitrogen-fixing crops also known as legumes, which convert nitrogen from the air into a form that is biologically useful. Legumes have a long history of cultivation in Scotland, and this briefing captures the current state of confident knowledge on their renewed potential.

Key findings

- There are two main categories of legumes –
  - **grains** (e.g. peas, beans, soybeans, peanuts), which can be divided into those with high quantities of oil, and those, such as pulses, which are high in protein and starch.
  - **forage legumes** (such as clovers and vetches) for animal feed, either grazed directly or cut for hay or silage. These might also be used as 'cover crops', to protect the soil and trap residual nitrogen, acting as a natural fertiliser.
- If a legume is grown in place of another crop as part of a rotation and with no added fertiliser, the savings in terms of fertiliser-offset in that particular year will be 100 kg/ha for a spring cereal or 180 kg/ha for a winter cereal and about 200 kg/ha for winter oilseed rape. Additional benefits include the potential availability of nitrogen to the following crop, thus reducing further the need for synthetic nitrogen fertiliser. However, the ability to calculate total fixation and residual nitrogen in Scotland's soils and climates is currently limited.
- 80% of current demand for legume products in Scotland is imported, mainly for animal feed, but also for human consumption. There is limited opportunity to access commercial seed stock as current markets are focused on more-temperate climates.
- There is considerable potential for legume yields to be increased above the current Scottish national averages. However, evidence shows that annual yields are variable across Europe, which suggests low resilience of the crops in the face of unusual weather, such as the high rainfall of 2012-2013.
- The main constraint on legume production in Scotland is the absence of processing facilities: there are no dehullers, only one miller (small scale and pea mainly), and no dry- or wet-fractionation facilities to separate pulses into their protein and starch components.

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[1] https://www.theccc.org.uk/wp-content/uploads/2018/08/PR18-Chapter-6-Annex-The-Smart-Agriculture-Inventory.pdf , data available at: http://naei.beis.gov.uk/reports/reports?report_id=958

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What we learned

Introduction

Scottish agriculture accounts for almost a quarter of Scotland's greenhouse gas (GHG) emissions[2,3], and the application of synthetic nitrogen fertiliser accounts for around 25% of the GHG emissions from agricultural soils[4].

In the 2018 Climate Change Plan, the Scottish Government committed to a reduction in emissions from the use of synthetic nitrogen fertiliser. One approach to be considered is increasing cultivation of nitrogen-fixing crops also known as legumes, which convert nitrogen from the air into a form that is biologically useful. However, practical effectiveness depends upon several environmental and economic factors and whilst there is a long tradition of legume-use in Scotland, the evidence-base for the effectiveness of legume crops rests largely on research and experience in other UK and European contexts.

This report summarises the current state of knowledge on the practical effectiveness and potential of nitrogen-fixing crops for Scottish agri-food systems.

Current status of nitrogen-fixing crops in Scotland

What are legumes?

Legumes crops are able to derive their entire nitrogen requirement from atmospheric di-nitrogen gas. Almost all other crops draw nitrogen from the soil and require the addition of nitrogenous fertiliser, and most often in synthetic form. In addition, applied synthetic nitrogen fertiliser losses also contribute to GHG emission and diffuse water pollution. Therefore, as well as constituting high sources of protein- and carbohydrate-rich food for humans and animals, increasing the proportion of legumes in Scottish agriculture can reduce the need for synthetic nitrogen fertiliser, and associated nitrogen losses. Reducing synthetic fertiliser requirements of non-legumes is also achieved by virtue of either the high nitrogen residues left in-field after the legume crop harvest, or ecological processes which are realised when legumes and non-legumes are cropped together in the same space and time.

There are two main categories of legumes:

> **grain legumes** (e.g. peas, beans, soybeans, peanuts) – can be divided into two sub-categories based on whether the seeds contain significant levels of oil (i.e. lipid), or not. 'Pulses' comprise mainly protein, starch and very low levels, or no, oil (e.g. peas, beans, lentils). 'Oleaginous' types comprise protein, low levels of starch and relatively high quantities of oil (e.g. soybean, lupin and peanut).

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[2] CCC 2018. Reducing emissions in Scotland, Progress report to Parliament, Committee on Climate Change (including 2016). https://www.theccc.org.uk/wp-content/uploads/2018/09/Reducing-emissions-in-Scotland-2018-Progress-Report-to-Parliament.pdf , data at: http://uk-air.defra.gov.uk/reports/cat09/1806120917_DA_GHGI_1990-2016_v02-01.xlsx

[3] https://www.gov.scot/binaries/content/documents/govscot/publications/statistics-publication/2018/06/scottish-greenhouse-gas-emissions-2016/documents/00536542-pdf/00536542-pdf/govscot%3Adocument , data at : https://www.gov.scot/binaries/content/documents/govscot/publications/statistics-publication/2018/06/scottish-greenhouse-gas-emissions-2016/documents/00536736-xlsm/00536736-xlsm/govscot%3Adocument

[4] https://www.theccc.org.uk/wp-content/uploads/2018/08/PR18-Chapter-6-Annex-The-Smart-Agriculture-Inventory.pdf , data available at: http://naei.beis.gov.uk/reports/reports?report_id=958

forage legumes (such as clovers and vetches) – can be further sub-divided into 'forage legume crops' used in various ways for animal feed, and 'grass' which is either grazed directly or cut for hay or silage (e.g. clover-grass swards). Occasionally they are used as 'cover crops', to protect the soil and trap residual nitrogen, acting as a natural fertiliser.

Present status of cultivation of legumes in Scotland

Crop census data records collected since the 1850s suggest a systematic decline in cropped legume area to the present day[5]. The area of land growing grain legumes in Scotland is now very low by global standards. Census records together with information from the EU's Integrated Administration and Control System (IACS) indicate that two species of grain legume are cropped, faba beans and peas[6], each produced for both animal and human consumption (Figure 1). Peas and beans used for animal consumption have a wider distribution than crops for human consumption, the latter concentrated in high-input crop regions within a short travelling distance to processing plants. Peas for animal feed are grown over a particularly wide range of crop systems. However, forage legume crops such as vetches are no longer recorded in the crop census, and probably occupy a very small area, while forage legumes growing in grass swards (or in cover crops) are not recorded[7]. More research, and better data recording mechanisms, are necessary to discern the exact area of land given over to legumes, and the proportions and destiny of those which do enter the supply-chains. Such data can be used to estimate the amount of nitrogen derived from biological nitrogen fixation by legumes as well as the values of the commodities generated from those leguminous products.

[5] Findlay, W.M. (1925). Grassland in Scotland. Farm Crops, Vol 3, 37-177. London: Gresham; Paterson, W.G.R. (1925). Farm Crops, Vol 1, Grain crops. London: Gresham; Porter, J. (1925). Beans. Farm Crops, Vol 1, 270-281, London: Gresham.

[6] Beans from the genus *Phaseolus*, such as runner and French beans, are also grown in Scotland but only on a small agricultural scale and in gardens.

[7] Agricultural Statistics Scotland 1912-1978; Economic Report on Scottish Agriculture 1980-2017

Current land area used for legume production

Of the four categories of peas/beans grown for animal/human consumption, peas and beans grown for animal production having the widest spatial distribution across Scotland (Figure 1). It is possible, by following individual field records in the IACS dataset over a succession of years, to identify the crops that are grown in rotation with the four types of grain legume. This analysis revealed a range of six arable-grass crop rotation systems in which legumes are currently grown[8]. Peas for animal feed are grown over a wide range of crop systems, from 'Rotational grass' to 'Arable winter. In contrast, peas for human consumption are grown with mainly winter cereals and other high input crops including potato. Beans for animal feed tend to be grown in crop systems of intermediate intensity. These systems occupy tens of thousands of hectares, but each contains legumes at very low density (usually <1% of the arable and short-term grass).

Yields

The yields per unit area of most crops grown in Scotland have remained fairly static since the 1990s after a period of intensification, 1960-1990. The yield of legumes in census data seems to have reached its high point earlier, by the mid-1980s, since they have been static or even possibly reduced (for example, peas for human consumption). Annual mean yields of combining peas (for animal consumption) have varied mostly between 3 and 4 t/ha for the whole UK since the late 1980s but are slightly lower in Scotland. Yields of vining peas (for human consumption) are higher, at around 4.5 t/ha on average (but yields between these types may not be strictly comparable because of possible differences in moisture content). Legume yields tend to be lower than those of the spring cereals in recent years (e.g. national mean varying between 5.5-6.5 t/ha in Scotland), which could cause potential conflicts (see below). However, current scientific consensus is that legume yields are much lower (approximately one third) of their yield-potential, and so could be increased well above the current Scottish national averages.

[8] Rotational grass; Grass-arable (spring cereal); Arable spring cereal; Arable mixed cereal; Arable winter cereal; High input arable cereal.

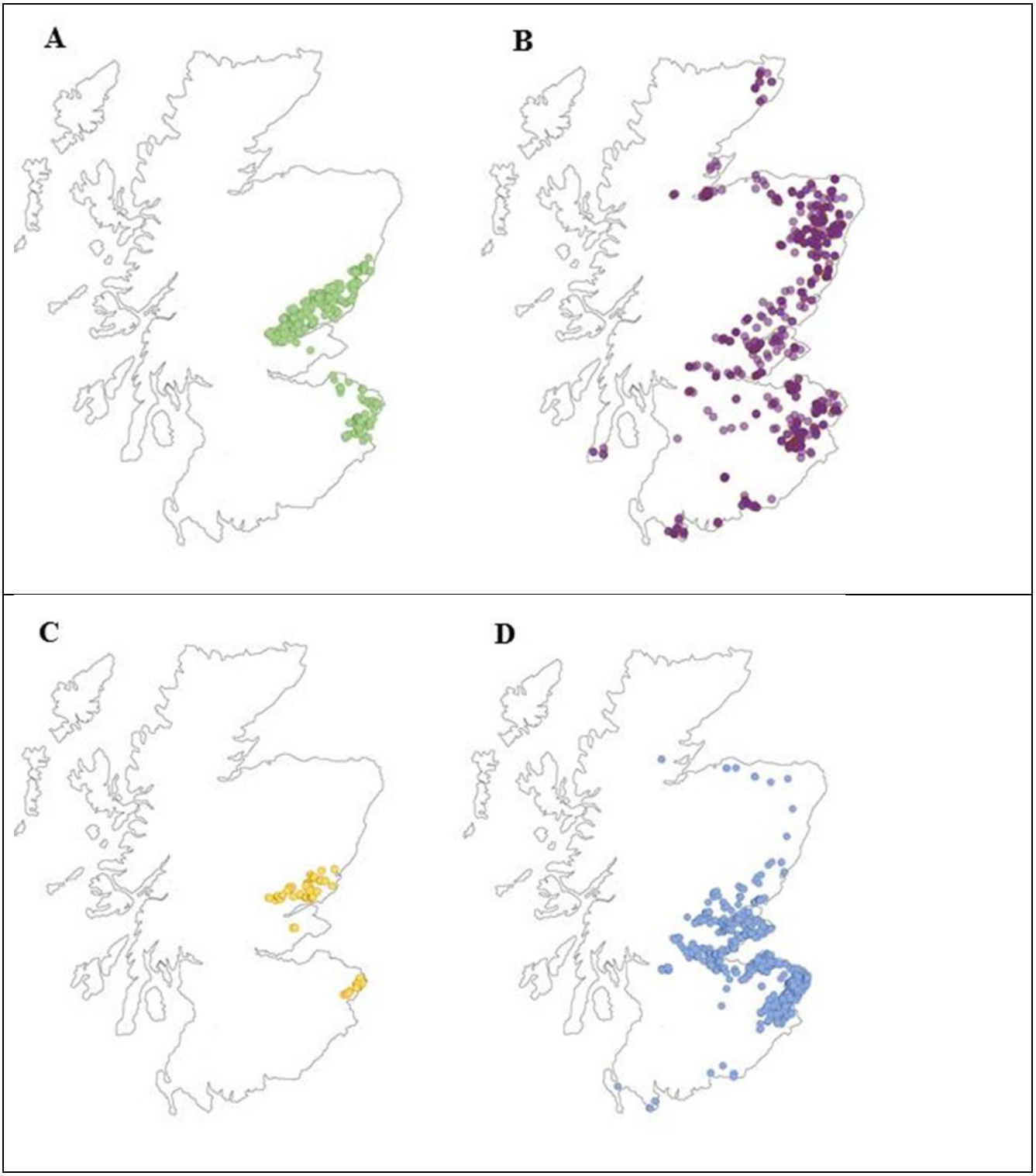

Figure 1: Current distribution of grain legumes in Scotland. **(A)** peas-human (green); **(B)** peas-animal (purple); **(C)** beans-human (yellow); **(D)** beans-animal (blue).

Climatic and soil requirements

Legumes tend to perform best in loam soils, with near-neutral pH and where water is not limiting. In this respect, they are like most other crops. A critical issue for grain legumes in Scotland is that early maturing varieties are required, especially for field beans. Variability in yield of legumes between years has become very large, a phenomenon detected in other parts of Europe, and is suggestive of an inherent instability in the underlying plant processes, possibly due to the poor resilience of the crops in the face of unusual weather such as the high rainfall of 2012-2013.

Nitrogen-fixing potential of legumes in Scotland

This is not something we can readily answer at present as these data are not currently systematically collected by growers. It is possible to extrapolate from the trials run at the James Hutton Institute's Centre for Sustainable Cropping (CSC) at Balruddery farm (near Dundee). In these trials, faba bean was able to fix 100 kg/ha of nitrogen on average, with a maximum of 400 kg/ha in one of the years studied to date (2011 until present). However, these would be considered upper limits as these trials were found to nodulate with efficient high-functioning rhizobia which were isolated from the root-nodules of the plants in those trials. There is insufficient data for other legume types at present to estimate their biological nitrogen fixing potential under Scottish growing conditions.

Mineral nitrogen requirement reductions by including legume crops

The average values of biological nitrogen fixation by faba beans in Europe are within the range of mean mineral nitrogen (fertiliser) inputs for typical cereal and root crops grown in Scotland. If a legume is grown in place of another crop (i.e. the legume receives no synthetic nitrogen fertiliser) as part of a crop rotation, the savings in terms of fertiliser-offset in that particular year will be 100 kg/ha for a spring cereal or 180 kg/ha for a winter cereal and about 200 kg/ha for winter oilseed rape. Applied to the six arable-grass crop systems identified in Scotland, synthetic nitrogen input over 5-6 years could therefore be reduced by between 77 and 84 % of the current input for that system (depending on the nitrogen requirements of the crop being replaced). These estimates refer simply to the nitrogen which is not used in that year where a conventional crop is substituted by a legume.

They do not account for the residual biologically fixed nitrogen left in the soil after the legume is harvested, which is potentially available to the following crop and thereby reducing its need for synthetic nitrogen fertiliser. Unfortunately, there are very few measures of total fixation and residual nitrogen in Scotland's soils and climates. Data from other continents are not directly applicable, since fixation rates depend on the legume crop, the other crops grown over a sequence in the same field, the specific types of native soil microbes (rhizobia), and the local pedoclimatic conditions. However, data from a recent EU-wide analysis suggested that legume residues typically account for 50-100 kg/ha nitrogen being deposited in-field in any year, the higher value being similar to the mineral nitrogen addition to a spring cereal crop in Scotland. At the time of writing, there is insufficient data to establish whether there would be differences across different varieties of nitrogen-fixing crops, or across the Scottish arable-farmed systems.

Expertise in growing legumes in Scotland – current state

On average, current legume varieties and management are not capable of achieving yields comparable to the cereals There is potential in increase nitrogen fixation capacity and yield of legumes further through dedicated education initiatives, breeding programmes and isolation of advanced rhizobia strains to be applied as seed treatments. Unfortunately, there are no current focused legume breeding programmes to support the development of optimised pea and bean varieties, or the selection of more novel types (e.g. lentil, common bean and soybean) nor their rhizobia, for consistent production under Scottish clines.

Current state of the market for these crops

Currently, the main markets for legumes in Scotland comprise: a) peas for freezing or canning; b) peas and beans harvested for grain or as whole crop for processing as animal feed (i.e. meat and fish production); and, c) a range of pulses grown as vegetables for human consumption. It is not presently possible to extract the current value of the market for these, as the data are largely held by private companies. At national (UK) level, the Food and Agriculture Organization of the United Nations (FAO) hold data on imports, exports and consumption, but extracting these and interpolating to the Scottish situation is not a trivial task and was not attempted in this review.

Most legume products used in Scotland (both for food and animal feed) are currently imported, i.e. 80% of demand and mainly for animal feed. Home-grown legumes therefore make a negligible difference to the overall nitrogen fertiliser requirements of agriculture and hence the GHG footprint. GHG emission factors for legume crops are low and estimated to be round 0.2%[9], and this is supportive supports the present IPCC GHG reporting procedure of assuming a zero-emission factor for BNF by legumes[10].

Scotland's reliance on legume imports comes with a cost to other countries. The import of certain products such as soya protein contributes to resource-use and serious damage to natural capital in South America for example. Therefore, increased production of legume crops in Scotland could dispense with these imports.

Do the benefits outweigh the constraints in terms of farming practice?

The potential benefits of legumes can outweigh the constraints. However, it must be acknowledged that the current agri-food system paradigm is characterised by a preference to cultivate non-legume crops types which demand high levels of synthetic nitrogen fertiliser. Such preference for non-legumes is driven by the more-consistent (and until recently) high yields, as demanded by supply-chains polarised towards processing the non-legume crops.

With the move to legume-supported agriculture, pursued as standard practice in organic and often mixed (arable plus animal production) systems, there is a move to reduced agrichemical dependency and greater environmental dependency. Under such environmentally dependant production, the best practices of legume-focused agronomy seek to encourage natural chemical cycling (and pest control) as much as possible. In turn, production is therefore a function of the extent to which the correct environmental conditions are achieved through management, as opposed to use of application of agrochemicals. This is a critical point, since with environmental dependency comes different demands. For example, the environmental- or ecological-approach is more highly knowledge dependent than conventional (non-legume) based approaches. In addition, the mitigation or adaptation to environmental dependency demands diversification of cropped systems, and their down-stream supply-chains sectors. A more diverse range of crops need cultivated differently, and this shift needs to be supported by the 'pull' generated by processors and consumers. Under legume-based systems greater gross margins and environmental benefits for the farmers are possible. However, to help ensure that the benefits of legume cropping consistently outweigh the constraints (or risks), support is necessary to encourage the transition of farming practices and supply-chain preferences from their current paradigm of high input

[9] Williams, M., Stout, J., Roth, B., Cass, S., Papa, V., and Rees, B. (2014) Environmental implications of legume cropping. Legume Futures Report 3.7. Available online: http://www.legumefutures.de/images/Legume_Futures_Report_3.7.pdf

[10] IPCC. (2006). 2006 IPCC guidelines for national greenhouse gas inventories, in: Eggleston, H.S., Buendia, L., Miwa, K., Ngara, T., Tanabe, K. (Eds.), Agriculture, Forestry and Other Land Use. Prepared by the National Greenhouse Gas
Inventories Programme, vol. 4. IGES, Japan.

dependency for a narrow range of non-legume crops, to environmental dependency for a broad range of crops, i.e. including legumes.

Opportunities and risks for increasing legume cultivation

Expanding and enhancing legumes within current systems

Adequate 'space' exists in each crop-system to allow expansion of legumes from their present 1 % to as high as 10% - 20%. Spring barley is the crop most likely to be substituted by a legume. There could also be some substitution of grass and winter crops, but expansion would lead to loss of little, if any, of the most profitable crops (e.g. winter wheat, potato, vegetables). If legumes were increased in area as single species monocrops, and the efficiency of legume cultivation remained as it is now, total biomass offtake from Scottish agriculture would decrease a little. However, there is evidence that legume yields can be increased above their current limit to virtually the level achieved by spring cereals if crops are managed according to best practice.[11] Legume intercropping, the growing of a cereal and a legume in the same field at the same time, is another opportunity for expansion as the legume does not fully displace the other crop. Whilst there is a likely decrease in the yield of the 'other' crop (estimated in the region of 30% for barley), there is an increase in the total yield of the two crops crop combined with this approach. There is also evidence that such approaches have additional benefits, e.g. biocontrol of pests, reduction of N_2O emission, and increased gross margins. A successful expansion of legume cropping would require support to generate the necessary scientific and technical knowledge and training for farmers.

New agricultural practices: mixtures, intercrops, living manures and under-sowings

Globally, intercrops of legumes and cereals (and other crops species) are widespread in agriculture, usually as row- or line- intercrops in many configurations (e.g. one row cereal, three rows legume). Traditionally, Scotland has grown legume-legume or legume-cereal sown mixtures rather than row intercrops. Mashlum – a sown mix of oats and beans (but it could be of any legume-cereal pair) – was still cultivated beyond the middle of the 1900s but is now very rare. Legumes were also deployed as under-sowings and nurse crops, usually to support cereal production. In all cases, the legume gave benefit. Research is ongoing in the current Strategic research programme with growers in Scotland aiming to assess the utility of row intercrops and living manures. Such stakeholder centred initiatives are also supported by EU funded innovation projects such as www.true-project.eu and www.plant-teams.eu. These projects are also capturing how farmers as early-adopters have transitioned to legume-supported systems. Reports from legume innovation network meetings has identified that the most common barrier to legume-uptake (beyond the global trade market) is a lack of access to unbiased knowledge and advice on crop choices, drilling and management, including which modern machinery and precision agriculture technology to access. On a practical-level there are also concerns regarding harvesting time, especially of faba beans being too late in some poor-weather years, or complexity of operations when intercropping.

Introduction of new grain legume species

There is potential to introduce or expand cultivation of species of grain legumes in Scotland, most notably:

[11] Researchers based as ADAS and Pulse Growers Research Organisation calculated for a set of 10 farm sites that if combinable pea crops used the solar energy available to them efficiently and avoided limitations of dryness, then the current farm yields could be increased almost three-fold from 3.7 t/ha (at 85% moisture) to 9.8 t/ha.

- Species of ***Phaseolus*** **beans** (e.g. French bean, runner bean): currently grown widely as a vegetable.; i.e. they are capable of growing as field crops in Scottish climates. Such beans are reported to be increasing in local vegetable schemes, although hard data are not available. There are no commercial Scottish varieties bred specifically for the local climate and there is no breeding programme in Scotland.
- **Lentils**: never grown on significant commercial scales in Scotland but demonstrated as a potential field crop in England.[12] Trials are also underway at the James Hutton Institute using lentil types bred for the colder climates of the alp foothills (in Germany). Marketing research is essential: lentils grown organically can fetch as much as £1200 per tonne in Germany.
- **Soybean**: an oil-bearing legume producing 70% of the world's grain legume output and the most balanced for animal feed in terms of nutritional profile. Current varieties are unsuited to the climate as a grain crop but have potential for high biomass production in Scotland as a forage crop. Current limitations include uncertainties regarding sufficient and stable yields, and yield qualities, as well also competition for global markets. Professional agronomists in Scotland have not (yet) developed the emerging opportunities in this sector.
- **Lupin**: an oil-bearing legume currently grown on a small scale in Scotland with current potential as a whole crop forage rather than grain legume. This is at least in part due to the lack of specialised processing facilities, since lupin is classified as allergenic dedicated facilities (for allergen containing crops) is preferred.

The future of forage legumes lies in reidentifying the value of species previously grown and reintroducing them into future agriculture rather than in seeking new species.

Market considerations opportunities

Specific varieties of existing crops, and more crop species, bred for Scotland's climatic and soil conditions are required to expand commercially successful growth and market interest in legumes. Due to the high percentage of legumes currently being imported, the UK market currently is not large enough to support commercial interest in varieties specifically adapted to Scottish conditions. Therefore, currently available commercial seed stock has been bred for more-temperate climates. To some extent, southern-UK based breeding stations are contracted by large breeding companies, and there are several academic programmes focused on species used for academic research purpose (*i.e.* non-food) legumes. In addition, changes in consumer preferences and societal awareness of the impact of imported legumes for food and feed requirements may provide further opportunities for growth.

Dietary change

Public attitudes to legumes as food are changing. The introduction of meat analogues (i.e. substitutes, surrogates or replacements for meat) in Western markets is a relatively recent development. Plant proteins are also increasingly promoted as a response to the demands of consumers and health professionals for versatile functional ingredients. Sales of pre-cooked and flavoured canned beans are increasing year on year and pulse-based product lines are recorded to have increased by 460% between

[12] Hodmedods Ltd, www.hodmedods.co.uk

2011-15 (Mintel 2015 & 2018). The potential of legumes in the highly lucrative healthy snack food market has not yet been developed widely by Scottish agri-businesses.[13]

Fractionation

For grain legumes, parts of the grain are worth more than the whole. Grain legumes which are separated into their component parts: dehulled to remove their skin; and fractionated to concentrate their carbohydrate and protein components; are of great commercial value since the isolated components are demanded by various industries (e.g. hulls for pet food, protein by aquaculture, starch for animal feed and industrial uses as well as processed human-food products).

Constraints

In expanding legume cultivation, it is critical that existing markets and supply chains are not compromised. For example, if legume expansion was to occur at the expense of barley cultivation, the implications for the bovine feed and alcohol industries that rely on barley products would need to be carefully considered. However, it is feasible that various forms of legume-supported systems could facilitate barley production with greatly diminished reliance on synthetic nitrogen fertilisers.

The main constraint on most potential legume products and markets, however, is the absence of legume processing facilities in Scotland: there are no dehullers, only one miller (small scale and pea mainly), and no dry- or wet-fractionation facilities to separate pulses into their protein and starch components. There are Scottish companies on the verge of investing in such capacities. If established, it would present a new Scottish capability that would benefit arable- and fish-farming and present sustainable food ingredients to support and diversity Scotland's existing food and drink industries. There are also some products based on home-grown grain legumes, for which markets may be relatively small, but the technical infrastructure is already present. For example, beer made from home-grown faba beans is already on the market and bread made partly with bean flour is at the stage of design and trialling.

Conclusions

There is currently only a very small area of land given to legume production. While there are insufficient data on the nitrogen fixing potential of the individual species currently grown in Scotland, data from the first trials using faba beans suggest that legumes provide significant savings in nitrogen fertiliser use if grown as part of a crop rotation. This benefit occurs not only in the year in which the legume crop is grown but also extends into the next phase of the rotation through residual biologically fixed nitrogen left in the soil after the legume is harvested and which is available to the next crop. Savings will be made in mineral nitrogen usage and, therefore, GHG emissions. Unfortunately, there are no data to quantify the extent of biological fixation at present in Scottish cropping systems. The benefits can outweigh the constraints if the best management is used. However, the demise of independent agricultural extension services means the knowledge void cannot be easily filled. Farmers often have production units specialised for non-legume-based commodities, meaning that additional investment is required to enhance legume production.

There are a number of areas with uncertainty. There is a serious dearth of knowledge on the occurrence of legumes in rotational and permanent grass and their contributions to nitrogen offset, productivity and biodiversity, including support for insect pollinators. Transitioning from cropping systems that depend on synthetic nitrogen to ones based on biological nitrogen fixation by legumes requires support from a

[13] James Hutton Institute-coordinated reports on the market potential are on-going, and readers are directed to Deliverables of EU-TRUE project Work Package 4 (WP4), Markets and Consumers - https://www.true-project.eu/publications-resources/deliverables/ .

series of interventions and developments that range from research and education to supply-chain capacities and consumer preferences. Ultimately, however, the main stimulus must come from increased demand for home-grown legume-based products, followed by trialling and introduction of new agronomy and new crop species (e.g. lentil, soya).

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