1 Introduction – Perspectives on Legume Production and Use in European Agriculture

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Abstract

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

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

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

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

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

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

Producing Legumes

Grain production systems

Grain legumes are produced in a variety of ways across Europe, including as dry grain, green forage, arable silage and green manure, with the choice often depending on climatic and edaphic conditions as well as intended end-use. Several species are grown in Europe, some with both spring-sown and autumn-sown variants. The main species are pea (*Pisum sativum* L.), lupins (*Lupinus* spp.), faba bean (*Vicia faba* L.), chickpea (*Cicer arietinum* L.), lentil (*Lens culinaris* Medik.), common bean (*Phaseolus vulgaris* L.) and soybean (*Glycine max* (L.) Merr.). Although soybean is officially classified by the Food and Agriculture Organization of the United Nations (FAO) as an oilseed crop rather than a protein crop, it has a similar function in cropping systems to the other grain legumes and is the reference protein crop, so we include it here. Grain legumes are most commonly produced as sole crops, although there is currently great interest in intercropping (Malézieux *et al.*, 2009). Cereal/legume intercrops can be grown for grain or silage, the latter as a way of boosting the forage protein content of livestock diets (Anil *et al.*, 1998) mainly under wetter conditions in northern and western Europe, and in some situations have a higher and more stable gross margin than the mean of the sole crops (Bedoussac *et al.*, 2015).

Forage production systems

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

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

Nutrition – Humans and Livestock

Grain legumes are important in the human diet in providing protein, essential amino acids and nutrients through direct consumption and indirectly through meat, fish, milk and eggs. Current nutritional guides such as *The Eatwell Guide* in the UK (Public Health England, 2016) and the Finnish National Nutrition Council (VRN, 2014) suggest decreased consumption of animal protein and increased use of vegetable protein, particularly from food legumes. Grain legume seeds contain protein, energy in the form of starch or oil, dietary fibre, micro- and macronutrients, vitamins and numerous bioactive phytochemicals (Strohle *et al.*, 2006), such as flavonoids and other antioxidants (Scalbert *et al.*, 2005). They provide dietary iron, zinc and calcium, all of which are important for humans and monogastric animals, but the availability of these nutrients is reduced by chelation to inositol hexa*kis*phosphate (phytate). There is increasing interest in the use of preparation procedures such as germination and fermentation to enhance both macro and trace element availability (Humer and Schedle, 2016). The protein content of grain legume species ranges from 20% in common bean and lentil to 40% in soybean and yellow lupin (see Chapter 5, this volume). This compares with 7–17% in cereals and 17–26% in rapeseed (Day, 2013). There are significant positive effects on human health when animal proteins are replaced by plant protein including lowering cholesterol (Harland and Haffner, 2008), controlling hypertension (Harland and Haffner, 2008) and improving cardiovascular health (Sirtori *et al.*, 2009). Eating soybean and lupin can decrease cholesterol in humans (Sirtori *et al.*, 2012), and grain legumes may also be useful in the diet of diabetics (Bertoglio *et al.*, 2011) and in maintaining a healthy weight (McCrory *et al.*, 2010). A role in prevention of some cancers has also been suggested (Campos-Vega *et al.*, 2010). There is a large body of research on the health benefits of pulses (the starchy grain legumes), including a special issue of the *British Journal of Nutrition* in 2012 (volume 108, Supplement S1).

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

Legumes have the potential to replace part or all of the fish meal in the diets of farmed fish and the potential of a range of plant-based protein sources was recently reviewed by Ayadi *et al.* (2012). Grain legumes are a suitable feed for herbivorous fish such as carp (*Cyprinus carpio*), but a variety of legume-based extrudates can substitute for the fish meal normally used for many farmed carnivorous fish and crustaceans (Trushenski *et al.*, 2006). Soybean, particularly in high doses, can reduce growth rate due, at least in part, to antinutritional components (Kroghdahl *et al.*, 2010), but work is underway to breed new lines of soybean specifically for aquaculture (Herman and Schmidt, 2016). Compounded fish feeds contained a mean of 25% soybean meal in 2008, representing 4.5% of world soybean meal production in that year, and a trend was detected for increased use of other pulse and cereal proteins (Tacon *et al.*, 2011). There are numerous studies in the literature focusing on determining the best grain legume protein, and its optimal proportion in the diet, for different fish. For example, rainbow trout grew well on up to 30% narrow-leafed lupin meal (Glencross *et al.*, 2008). Faba bean or pea flour can replace some of the wheat or other cereal starch in the formulation of feed pellets under heat extrusion. Blending of different protein sources into a mixture is also common, as it balances the amino acid composition and dilutes the antinutritional effects of individual components (Gomes *et al.*, 1995). These aspects were reviewed in a Legume Futures report on novel feed and non-food uses of legumes (Stoddard, 2013).

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

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

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

Non-food Uses of Legumes

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

Bioenergy

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

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

Intercropping bioenergy grasses with legumes can reduce N fertilizer requirements. In North America, switchgrass (*Panicum virgatum* L.) yield was not significantly affected by selected legume intercrops, particularly lucerne where soil fertility was low, but N fertilization was greatly reduced or eliminated (Wang *et al*., 2010; Butler *et al*., 2013). Comparable datasets from Europe are scarce, but at high latitudes, the N fertilization requirement of reed canary grass (*Phalaris arundinacea* L.) can be reduced by mixed cropping with *Galega orientalis* Lam. with a mild reduction in yield (Epie *et al*., 2015). Use of BNF in this way generally reduces nitrous oxide (N_2O) emission, contributing to GHG mitigation.

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

Phytoremediation

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

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

Sunn hemp (*Crotalaria juncea* L.) produces long fibres that can be used in similar ways to hemp or jute (Ingle and Doke, 2006), along with pyrrolizidine alkaloids that can bioremediate nematode-infested soils, making it a potentially valuable multi-purpose crop. Field experiments in many warm climates have demonstrated the resistance of *Crotalaria* species to root-knot, root-lesion and other nematodes that parasitize crop plants. Laboratory studies have shown that the alkaloids from sunn hemp species paralyse some nematodes and arrest the development of others (Subramaniyan and Vadivelu, 1990; Jourand *et al.*, 2004; Curto *et al.*, 2015). Sunn hemp can be used as a green manure to control nematodes in field (Curto *et al.*, 2015) and greenhouse (Lajudie *et al.*, in preparation, reported by Stoddard, 2013) production of vegetables.

Legumes in Crop Rotations

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

A legume influences following crops through a set of 'break-crop', 'nitrogen' and 'legume-specific' effects (Chalk, 1998; Peoples *et al.*, 2009). The break-crop effect occurs when a cropping sequence lacking diversity, such as the continuous production of small-grain cereals (wheat and barley) typical of most of Europe, is 'broken' by a broadleaved crop or a ley (Robson *et al.*, 2002). The most important part of the effect is the reduction in soil-borne diseases of cereals (Kirkegaard *et al.*, 2008), while other components include the removal of hosts of other pests and the opportunity to use alternative methods and agrochemicals for pest, pathogen and weed reduction (Prew and Dyke, 1979; Stevenson and van Kessel, 1997) and improvements in soil structure (Chan and Heenan, 1996). The nitrogen effect is the release of biologically fixed N from legume residues, the rate of which is affected by their relatively low C:N ratio, and the impact on the following crop is clearer in sandy than loamy soils (Jensen *et al.*, 2004). The key part of the legume-specific effect is the enhanced growth of plant growth-promoting bacteria (Lugtenberg and Kamilova, 2009), particularly hydrogen-fixing bacteria (Maimaiti *et al.*, 2007), contributing to the improved growth of the following crops such as broccoli after narrow-leafed lupin (Thorup-Kristensen, 1993). The taproot architecture and coarse lateral roots of grain legumes, in contrast to the fine network of cereal roots, assist water infiltration and form channels followed by the roots of the subsequent crop, but may also affect leaching (Dunbabin *et al*., 2003; Neumann *et al*., 2011). The N content of the legume residues influences the potential for nitrate leaching and N_2O emissions (Pappa *et al*., 2011), increasing the value of an N-retaining cover crop, particularly when the following crop is spring sown, leaving a winter fallow (Tuulos *et al*., 2014). When used as a cover crop, a grain legume can supply N to the following crop while protecting the bare soil, and mixtures of legumes with other crops further reduce leaching potential (Tosti *et al*., 2014), with vetches being the most cost-effective (Büchi *et al*., 2015). N and phosphorus losses, and ways to limit them, are covered in greater detail in Chapter 3, this volume. The impacts of legumes on biodiversity are reviewed by Everwand *et al*. (Chapter 4) in this volume.

Current Perspectives on Legume Production

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

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

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

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

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

Continued

Table 1.1. Continued.

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

[a]GM, Genetically modified.

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

Country	Institution[a]	Primary purpose of the field experiment[b]	Environmental impacts investigated
Denmark	Aarhus University	Organic/conventional cropping comparison including dairy, mixed cropping, rotations, assessment of leaching, GHG and NH_3 emissions (three sites)	N cycling
Finland	University of Helsinki	Rotations, crop diversity, intercropping	Bioremediation, multifunctionality
Finland	LUKE	Organic/conventional cropping comparison with and without livestock, green manure, leaching	Multifunctionality
France	CIRAD	Green manure in greenhouse vegetable production	Biological control of nematodes
Germany	ZALF	Organic dairy farming	Weed reduction, nutrient dynamics
Germany	Von Thünen Institute	Mixed organic cropping, rotations, whole-crop silage, leaching assessment	N cycling
Greece	Agricultural University of Athens	Organic/conventional cropping comparison	Salinity management
Ireland	Teagasc and Trinity College Dublin	Mineral N vs BNF, N flow, life cycle assessment, leaching	Biodiversity, disease cycles, N cycling
Italy	Università Mediterranea di Reggio Calabria	Legume–cereal intercropping	N cycling, biodiversity, multifunctionality
Poland	IUNG-PIB	Organic/conventional ('integrated') cropping comparison, crop rotation	N cycling
Romania	Agricultural University of Romania at Fundulea	Organic cropping; cultivars for organic systems	N cycling, biodiversity
Spain	University of Córdoba	Rotations, tillage; broomrape control	N cycling, disease cycles, C sequestration
Sweden	SLU	Rotations; non-dairy systems (three sites)	Disease cycles, N cycling
UK	SRUC	1: Organic rotation; stocked and stockless systems, GHG exchanges; 2: Synthetic nitrogen sources; GHG exchange	Nutrient dynamics
UK	James Hutton Institute	Stockless, arable rotations, conventional and alternative strategies for nutrient supply	N cycling, biodiversity, disease cycles, multifunctionality

[a]CIRAD, Agricultural Research Centre for International Development; IUNG-PIB, Institute of Soil Science and Plant Cultivation; LUKE, Natural Resources Institute; SLU, Swedish University of Agricultural Sciences; SRUC, Scotland's Rural College; ZALF, Leibniz Centre for Agricultural Landscape Research.
[b]BNF, Biological nitrogen fixation; C, carbon; GHG, greenhouse gas; N, nitrogen; NH_3, ammonia.

risk along with the gross margins of crop production including pre-crop effects in a modified rotation generator (Reckling *et al*., 2016a) and extended to five sites (Reckling *et al*., 2016b). On average, N_2O emission was reduced in legume-supported systems by 18% (arable) and 33% (forage), while nitrate leaching potential was reduced by 24% and 38%, respectively). Gross margins were improved by legumes in all three forage test cases, but in only two of the five arable test cases (Reckling *et al*., 2016b). Novel rotations were generated that provided higher potential gross margins than the current general practice. Related economic aspects of using legumes in European agricultural systems are covered by Preissel *et al*. (Chapter 13, this volume) and the attendant policy issues by Kuhlman *et al*. (Chapter 14, this volume) in this volume.

Conclusion

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

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