Legume-supported cropping systems for Europe

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GENERAL PROJECT REPORT

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Legume Futures

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This general report was first prepared at the end of the research period (2010 – 2014) at a time when some results were not yet formally published. It will be revised further as further results are published.

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Legume Futures Reports

Complementing this general project report and the academic publications, the consortium's work is published in a series of monographs. These are:

Stoddard, F.L. and Williams, M. 2011. Sampling and measurement protocols for field experiments assessing the performance of legume-supported cropping systems. Legume Futures Report 1.1.

Stoddard, F.L. 2013. The case studies of participant expertise in Legume Futures. Legume Futures Report 1.2.

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Baddeley, J.A., Jones, S., Topp, C.F.E., Watson, C.A., Helming, J. & Stoddard, F.L. 2013. Biological nitrogen fixation (BNF) by legume crops in Europe. Legume Futures Report 1.5.

Williams, M., Stout, J., Roth, B., Cass, S., Papa, V., and Rees, B. 2014. Environmental implications of legume cropping. Legume Futures Report 3.7.

Topp, K., Watson, C., Papa, V. Williams, M., Stout, J., Cass, S., Fischer, J., Böhm, H., Murphy-Bokern, D., Kuhlman, T., Stoddard, F.L. Lindström, K., Reckling, M., Preißel, S., Bues, B., Zander, P., Knudsen, M.T., Olesen, J.E., Hermansen, J.E.M., Schelde, K. 2014. Policy implications of the environmental and resource effects of legume cropping. Legume Futures Report 3.8/6.6.

Schläfke, N., Zander, P., Reckling, M., Hecker, J.-M. Bachinger, J. 2014. Evaluation of legume-supported agriculture and policies at farm level. Legume Futures Report 4.3.

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Kuhlman, T., Linderhof, V., 2014. Social Cost-Benefit Analysis of legumes in cropping-systems. Legume Futures Report 4.6.

Murphy-Bokern, D., Watson, C.A. Stoddard, F., Lindström, K., Zander, P., Reckling, M., Preisel, S., Bues, A., and Torres, A. 2014. Outlook for knowledge and technology for legume-supported cropping systems. Legume Futures Report 5.3.

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SUMMARY

Legumes have historically played a central role in European agriculture providing high protein pulse grains for food, fixing nitrogen to support crop growth and providing feed for livestock in the form of forage and grains for inclusion in concentrate feed. Grain legumes are now grown on only 1.8% of arable land in Europe compared with on 4.6% fifty years ago. In the forage sector, legumes have largely given way to heavily fertilised grassland over the same period. This sits against a growing European demand for meat and an increasing reliance on imported soya for livestock production. The Legume Futures project set out to deliver knowledge and technology for the optimisation of the use of legumes in European agricultural systems and promote the partnerships needed to achieve this. We used a combination of case studies, modelling and new data to improve understanding of crop rotations and farming system for improved legume production. We have assessed ecosystem services delivered by legumes and the economics of legume production across the EU. Fundamental to the wider and longer term impact of the project, we also have addressed the policy background and options.

Using an extensive network of 18 case studies in 12 countries, the Legume Futures project has evaluated the current status of legumes in European farming systems and evaluated the economic, evironomental and resource effects of new and novel cropping systems in which legumes are a component. The case study approach helped us to understand the current state of legume production in different agroclimatic zones and the effects of legumes in cropping systems and perceived barriers to production. This was achieved partly through discussion with an extensive network of researchers, advisors, producers and NGOs. A second approach brought together insight gathered from the network of 18 long-term and well-documented experiments. The accumulated intelligence from both these approaches was used to develop biophysical and economic models of cropping systems at both the farm and regional scales. Using five contrasting regions of Europe (Eastern Scotland (UK), Calabria (IT) Sud-Muntena (RO)) Västergötland (SE) and Brandenburg (DE)), a rigorous analysis of existing and new rotational designs was undertaken to explore the economic and agronomic implications of new system designs. In the majority of cases, rotations that included legumes were more profitable than those that did not. However, in Sweden and Germany the legume based rotations were less profitable and considered by farmers to represent a higher risk than conventional non-legume based rotations. Thus at current estimates of crop values and input costs, it is already economic to include legumes in rotations in many European conditions. The legume sometimes took the form of an additional crop in the rotation and sometimes as a direct replacement for another crop. The generated rotations reflect the observations from different regions of the

"pre-crop" or "break-crop" effect of legumes on yield, N uptake, quality and crop health of following crops.

Cereals following a legume crop can yield up to 25% more than continuous cereals and our research suggests that this is largely due to processes influencing nutrient uptake and pest and disease control. The magnitude of this effect varies with species, for example, high-biomass crops such as faba bean generally give a greater effect than low-biomass crops such as chickpea. Site also influences this pre-crop effect. The greatest effects of introducing legumes are seen in areas which have predominantly cereal based rotations e.g. Poland and Northern Italy.

Policy measures currently available within the Common Agricultural Policy were shown to have a limited scope for increasing cultivation of legumes in arable farming. Modelling the impact of potential European policies up until 2020 showed that a 'Legume Premium Payment' would offer the best opportunity to halt the decline in cultivation of grain legumes.

The case for expanding legume production in Europe is commonly based upon supposed resource use and environmental benefits (substitution of fertiliser N, reduced greenhouse gas emissions, improved biodiversity etc.). The Legume Futures project directly assessed these impacts. Biological nitrogen fixation (BNF) occurs in legumes as a result of a symbiotic relationship between the plant and microorganisms. In the literature there are a range of estimates of the importance of nitrogen fixation as an input to the European nitrogen cycle. Most published estimates have simply multiplied crop area by BNF *per* unit area. Our re-analysis of existing literature to additionally take into account variation in crop yields across Europe has shown that 811 Gg of N (0.811 million tonnes) was fixed in the EU27 by agricultural legumes in 2009. The total amount of N fixed by forage legumes was 586 Gg, comprising 414 Gg from permanent pastures and 172 Gg from temporary pastures. For grain legumes, the total fixation of 225 Gg was dominated by pea, faba bean and soya bean, which were responsible for about three quarters of N fixed.

The losses of nitrous oxide from legume and non-legume based systems were studied in both forage and grain legumes addressing a recognised knowledge gap in this area. We measured nitrous oxide emissions across a range of sites, legumes and following crops using an agreed protocol and focussed on quantifying the proportion of nitrous oxide released from the nitrogen fixation process and the emission intensity (the amount of nitrous oxide emitted per unit of crop produced). Through this research we have established that the use of legumes (both grain and forage) within farming systems can significantly reduce nitrous oxide emissions and emission intensities. The overall average emission factor for nitrogen fixed by legumes was 0.14 % (compared to 1% for fertiliser N) resulting in an annual flux of N_2O of 0.41 kg N_2O-N ha^{-1} for faba bean and 0.54 kg N_2O-N ha^{-1} for peas. This is approximately 40 to 50% of the default background flux of N_2O used by the IPCC to account for mineralisation of crop residues and atmospheric deposition. A continental scale analysis using life cycle assessment techniques undertaken within Legume Futures compared the GHG emissions for legumes grown in Europe with those grown elsewhere. The overall impact of producing more grain legumes in Europe includes a small climate benefit compared to importing soybeans to Europe. Approximately 280 kg CO_{2eq} are avoided for each hectare producing pea instead of wheat in Europe. Similarly, 175 kg CO_{2eq} are avoided for each hectare of faba bean produced instead of wheat in Europe.

In order to quantify the impact of legumes on biodiversity we measured impacts on non-crop vegetation, earthworm, ground-active invertebrate and *Carabidae* communities, as well as soil fauna feeding activity across our network. Although there were differences between sites and crops, there was no consistent effect of the inclusion of legumes within a system on biodiversity.

Legumes have also evolved many biochemical mechanisms that protect them from herbivores, and the bioactivity of these compounds makes them suitable for many novel and non-food purposes, including the provision of novel livestock feeds, phytoremediation. A review of novel and non-food uses of legumes demonstrated their value for a range of uses as new animal feeds and non-food purposes. In the wild, biological nitrogen fixation is a characteristic of pioneering plant communities and this characteristic is provided by the legume species. Linked to this, legumes can play a special role in improving the agronomic quality of soils that are marginal to agriculture.

The Legume Futures project will provide a valuable resource on which to base future research and policy decisions. The project itself and the reports produced by the project are available from the project website at www.legumefutures.de . The European Legume Resource Centre (or ELRC), provides access to a range of related resources and may be accessed at www.elrc.eu.

INTRODUCTION

Bob Rees and Christine Watson, SRUC, UK

Goals and approach

It is well established that legume crops contribute more to the farming system than simply the harvested part: they fix atmospheric nitrogen into forms available for plant metabolism, they break the cycles of diseases that attack the major cereal crops, and they can replace other food, feed, fibre and fuel crop products that are imported from other continents. Nevertheless, they are under-represented in European agriculture, and Legume Futures aimed to investigate the underlying reasons. Legume Futures set out to understand the development of legume-supported cropping systems that would improve the environmental impact of European agricultural systems. It also aimed to support public policy and related economic objectives: reducing fossil energy inputs into agriculture, nitrogen emissions to the environment, and the global environmental impact of European agriculture; increasing the economic competitiveness of legume crop and forage production in Europe, and contributing to the development of sustainable European agricultural production systems more generally. At the outset, the research concept comprised a set of interacting components (Figure 1).

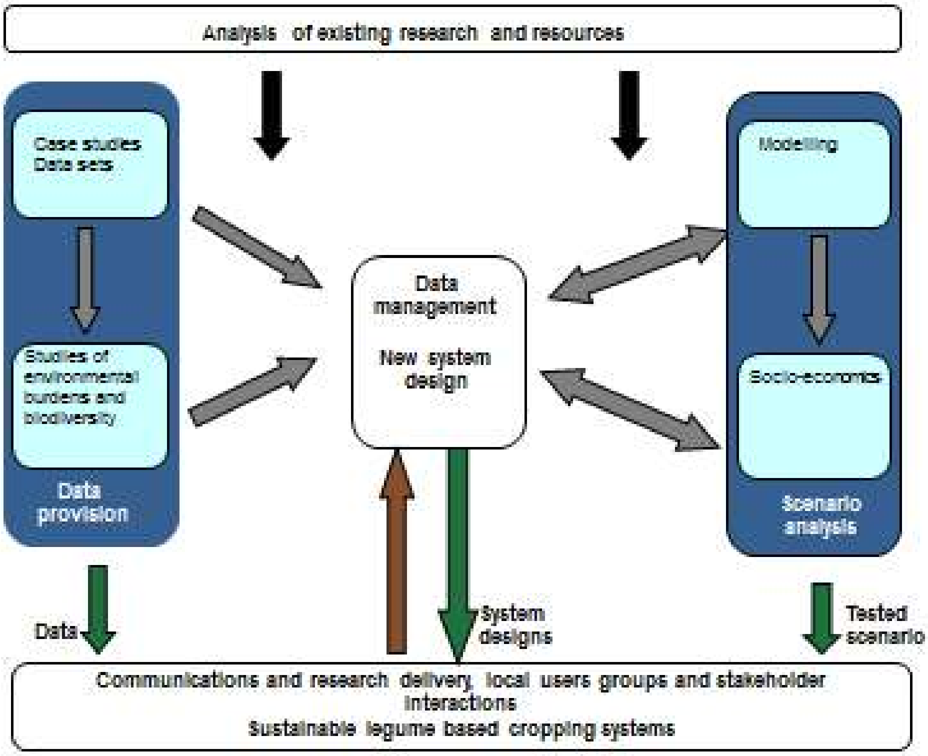

Figure 1. An overview of the Legume Futures project

We drew on a network of 18 existing field research sites across a wide range of agricultural regions of Europe. The network was been carefully selected to cover a wide variety of agro-economic and pedo-climatic zones across Europe (Figure 2), and also covers a range of different uses. By utilising 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.

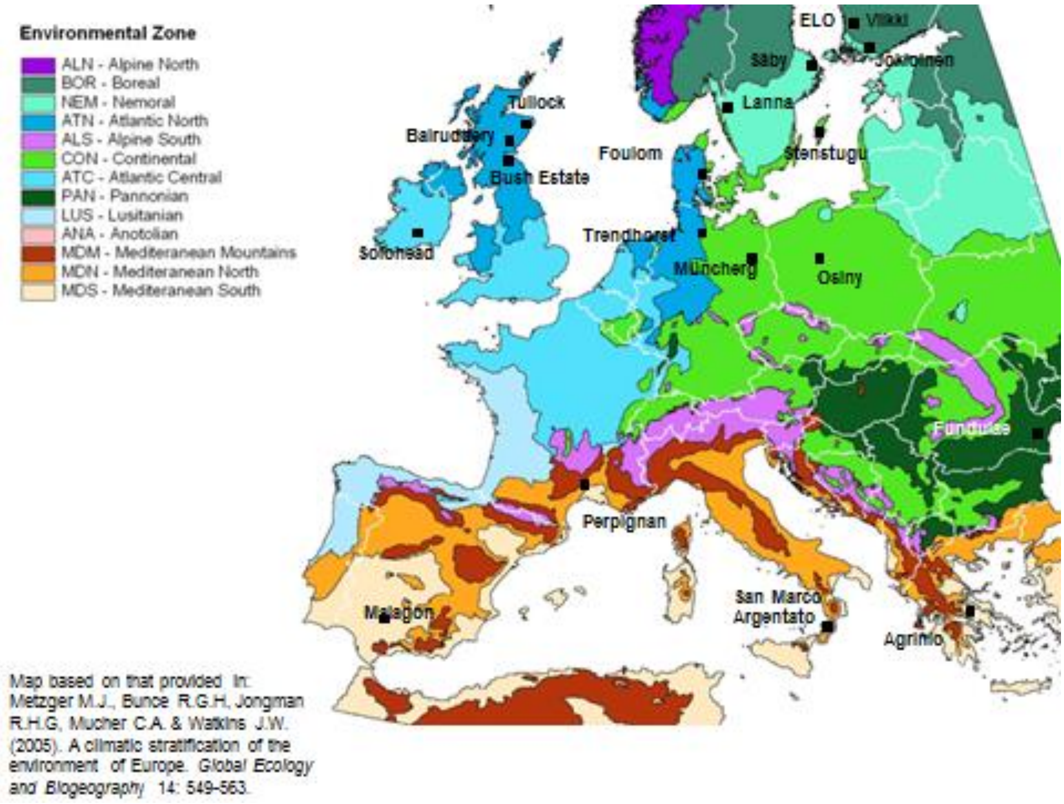

Figure 2. Agro-environmental zones of Europe according to Metzger et al. (2005) with locations of the Legume Futures field experiments.

Research and development objectives

We set out to identify the risks and benefits of the cropping systems for farm businesses at a range of scales across Europe major agricultural pedo-climatic zones, and support assessments of impacts for the wider agricultural economy and environment. Agricultural policy that more explicitly couples public support to environmental outcomes (‘public money for public goods’) may also play a role and a significant part of our research set out to inform policy development. The key to relevant farm level change is identifying the whole system risks and benefits of legumes from a farm business perspective. This needs to be complemented by support policies built on a more complete understanding of the consequences of these new systems for the environment at scales ranging from the local to the global. To support the required technical change and policy development, our research objectives were:

1. To conduct 18 case studies across Europe based on established field experiments which inform and validate new cropping system designs and

provide a focal point for the local development of the role of legumes in new cropping systems.

2. To design new cropping systems for Europe's pedo-climatic zones using modelling drawing on data from the case studies networked by the project.

3. To quantify, by using biophysical and economic models, the resource use (e.g. fossil energy), along with the socio-economic and environmental effects of contrasting cropping and agricultural system scenarios at a range of scales (from local to global).

4. To identify the wider environmental effects (e.g. carbon and nitrogen cycling, greenhouse gas emissions, soil quality, biodiversity, effects on pests and diseases) of legume use within farming systems, including systematic measurements of nitrous oxide emissions.

5. Drawing on data from existing and new field experiments and stakeholder interaction, to assess elite germplasm of a wide range of legume species and their symbiotic organisms with respect to their suitability in the new cropping systems.

6. To provide assessed scenarios to support the development of supply chains, including livestock feeding systems (for ruminants, monogastrics, poultry, and fish), based on these cropping systems in conjunction with ongoing research in the Consortium, input from our local and international Stakeholder Fora and the wider literature.

7. To provide a comprehensive and full assessment of the potential of legumes in the non-food sector and the implication of this potential for the design of cropping systems.

8. To facilitate access to the wider knowledge base on legumes and disseminate information on new agronomic, environmental and social impacts of legumes in farming systems.

9. To develop and enhance legume knowledge resources through the collection and linkage of data and knowledge leading to the establishment of a European Legume Crop Biological Resources Centre.

These project objectives were pursued in six work packages: Case studies of cropping systems; data management and novel system design; environmental impact; socio-economics; biophysical modelling; and knowledge interaction and research delivery. Within the first year of the research, we identified seven key research outputs upon which the impact of our research would be founded. These were: new cropping system designs; case studies; enhanced access to information/technology; environmental emissions and assessments; socio-economic data and assessments; resource use assessments; and assessments of non-traditional uses. This general project report is framed around those outputs.

LEGUMES IN FARMING SYSTEMS

Christine Watson, SRUC, UK

This section explores the role and agronomic challenges of both grain and forage legumes in agricultural systems in Europe. Grain legumes are grown as components of crop rotations, often providing a “break” from pests and diseases as well as supplying nitrogen to the following crop (Robson et al., 2002, Kirkegaard et al. 2008). They are grown as either sole crops or intercropped with cereals, and in the latter case generally ensiling for feed rather than harvested for grain. Forage legumes are grown as components of temporary pastures (leys) or in permanent grassland, and unless grown for seed, they are generally in mixtures with grasses, other legumes and forbs. In many cases, more than one species or cultivar of a legume will be grown within the mixture to provide the desired forage characteristics, e.g. to provide protein through the season.

In developing cropping systems with grain legumes, there are questions to address about the production of the grain legumes themselves as well as cropping system development issues. Improving yield stability in grain legumes is widely accepted as a challenge for both breeding and agronomy (Sass 2009, Flores et al. 2012). For the grain legumes, requirements include the ability to compete against weeds, lodging and nutrition. Kiær et al. (2012) showed the potential of mixtures of cereal cultivars to confer yield stability benefits over single cultivars, and although mixtures have not been widely explored in grain legumes, the same benefits could occur and be useful in situations such as feed production. For many decades, faba bean cultivars were "synthetic" or "composite", comprised of 2-4 moderately inbred lines that were then allowed to cross-pollinate for 2-3 generations, but this did not contribute to yield stability and recent cultivars are genetically more uniform (Torres et al. 2011).

Weed competition has a major effect on grain yields (Corre-Hellou and Crozat 2005) because most grain legumes establish relatively slowly and compete poorly against weeds at this stage. Manipulating plant density, under-sowing and intercropping are all options (Hauggaard-Nielsen et al. 2008, 2012). Legumes and non-legumes are often grown together in intercrops to combine the ability of the legume to fix nitrogen with the yield characteristics of the non-legume. The interactions between the species grown together may be positive or negative in terms of overall grain yield by influencing factors such as lodging and competition for resources. The interactions caused by interspecific competition need to be taken into account before recommending any intercropping with grain legumes. Intercropping research has been neglected in temperate agro-ecosystems due to its complexity and lesser relevance in cropping systems that rely on agrochemicals. Likewise, the limited agronomy research on how fertiliser applications can affect this interaction often remains inconclusive due to the complexity of the systems involved. Genetic and agronomic improvements need to proceed hand-in-hand, as new cultivars often require changes to agronomic practices in order to optimise productivity (Siddique et al. 2012), including quality aspects for both human and livestock consumption.

There is a worldwide trend towards simplification of cropping systems with fewer crops grown, but these usually lead to lower individual crop yields (Bennett et al. 2012). Grain legumes have the potential to work as effective break crops in cereal-based rotations (Robson et al. 2002, Kirkegaard et al. 2008), although there are clear questions about the selection and agronomy of following crops to optimise the break-crop effect. Successful grain legume-supported rotations and intercrops may require strategic approaches to the use of synthetic fertilisers as well as the use of nutrients from mineralisation of organic matter. For example, many legumes mobilise phosphorus in soils by means of root exudates (Bais et al. 2006). Interactions with suitable rhizobia are also a key component of successful systems (Siddique et al. 2012). In many cases, inoculation of crops with an appropriate rhizobium is a key factor in establishment and yield, particularly in soils where related legumes have not been grown before. Jensen et al. (2010) highlighted the need to know more about suitable pre-crops for grain legumes. The production of grain legumes may extend northwards as growing seasons lengthen at higher latitudes (Stoddard et al. 2009).

Forage legumes are a vital source of protein for ruminants in EU agriculture and an important component of mixed and grassland systems. Forage legumes add to the protein provision by domestic grain legumes, and especially in wet regions where N losses are a major limiting factor, they are more important than home-grown protein crops as an alternative to imported soya. Forage is produced by permanent grasslands (pastures), temporary grassland leys rotated with arable crops, and by dedicated forage legume crops such as lucerne. Forage legumes are used in pasture in many extensive agricultural systems to replace the use of fertiliser nitrogen (e.g. on 15 M ha of Mediterranean grasslands with native legumes, Ledda et al. 2000).

The use of legumes in pasture presents special challenges and opportunities. Despite the low overall response of grass-clover pasture to synthetic nitrogen application (Bax and Schils 1993, Gonzalez-Rodriguez 1991), the use of high applications of synthetic fertiliser in pastures that contain or could contain clover is common, reducing the role of clover in forage production and the nitrogen nutrition of the whole system (Carlsson and Huss-Danell 2003, O'Mara 2008).

These challenges come on top of agronomic drawbacks. Clover often presents problems of lack of persistence and annually variable production (O'Mara 2008, Cavaillès 2009, Peeters 2010), although agronomic techniques are being developed for maintaining clover content (Humphreys et al. 2008). Red clover leys generally last 2-3 years, whereas white clover can last 15 or more (Humphreys et al. 2008, Stoddard et al. 2009). Excessive clover consumption in grazed swards can lead to bloat, the production of foam in the rumen, and this can be managed with appropriate mixtures of forage species (Peeters, 2010). Grass-legume mixtures provide significant agronomic benefits in terms of yield, agronomic quality, low input costs, and feed quality as compared to pure grass and silage maize, but have the disadvantage of slow growth in spring (Peyraud et al. 2009). Clovers can also lead to low efficiency of N use in the rumen as a result of an imbalance between degradable nitrogen and fermentable energy (Luscher et al., 2014). As well as influencing product quality (Dewhurst et al. 2003), legumes can lead to enhanced growth rate and milk yield in animals compared with pure grasses (Dewhurst et al. 2009), on account of enhanced intake rather than differential digestibility.

Dehydrated fodder production, including non-legumes as well as legumes, represents a niche for support that was created by the EU in 1974 to protect the fuel-based dehydration industry in times of increasing fuel prices, and to contribute to the supply of plant protein for livestock (Marrugat, 2001). The EU produces around 4 M t of dehydrated fodder each year (LMC International 2009). Dehydrated fodder production is an especially important agricultural sector in southern European countries and 92% of the Spanish dehydrated forage production area is of lucerne, mostly grown under intensive irrigation (Guerrero, 2010).

Forage legumes are an important source of protein for ruminants, so play a key role in integrating livestock and crop production, increasing the recycling of nutrients on farms and thereby reducing nutrient losses (Luscher, 2014). Forages fit readily into mixed farming systems with ruminants either on the same farm or nearby, but long-distance transport of either silage or hay is seldom economically viable. Traditional ley/arable rotations in cool temperate agriculture typically include 3–6 years of grass/clover leys to supply N fertility and livestock feed, and rotate them with other crops (Tivy, 1990). This type of rotation is still prevalent in organic farming, extensive production systems and regions where mixed farming is traditional. Mixed farming has a number of possible environmental advantages over specialised arable farming, including lower energy use for transport of home-produced feed, replacement of fertiliser by the effective use of manures, and infrequent ploughing.

Legumes play a role in agroforestry, such as Spanish silvopastoral systems. They combine grazing areas with forestry (predominantly oak trees), and cover about 4 M ha. Intensive and continuous livestock grazing (Olea and San Miguel-Ayanz, 2006) creates and maintains a high representation of several legume species such as subterranean clover (*Trifolium subterraneum*), and there are many self-sown legumes (e.g., 29 species in the Madrid region, González Bernáldez 1991). Forage legumes are often used in silvo-arable systems where trees such as olive or carob are combined with mixed ley-arable rotations (Eichhorn et al. 2006).

The importance of legumes in rotations

Increased yields of subsequent non-legume crops

Crops following a legume in rotation yield more than after many other pre-crops. Even where all crops are fertilised for optimum yield, cereal crops following 'break' crops are reported to yield 15 to 25% more than cereals grown continuously (Peoples et al. 2009b), due to reductions in diseases and improvements to root growth. This is a significant resource benefit and is greater after legumes than after other break crops (Table 1). Part of the yield benefit is caused by changes in soil microbiology, particularly the enhancement of growth of beneficial soil micro-organisms by hydrogen released from nitrogen-fixing root nodules (Maimaiti et al. 2007).

The nitrogen effect of legumes increases yields of subsequent crops further where they receive low or moderate levels of fertiliser. The size of this nitrogen-related yield benefit also depends on the species of the legume crop; high-biomass crops such as faba bean generally give a greater effect than low-biomass crops such as chickpea. Similarly, high-biomass legumes grown only for the residue (green manuring) provide a greater effect than the residues of legumes harvested for grain. This positive yield response persists and may affect a second or even third cereal crop (Evans et al. 2003). The size of the break-crop effect varies also with site characteristics, and is generally lower where growth of the break crop is restricted due to poor availability of water or nutrients (Bachinger and Zander, 2007; Kirkegaard et al. 2008).

The highest break-crop yield effects arise from introducing grain legumes in regions with high cereal proportions, such as above 75% (von Richthofen et al. 2006). In our analyses we note that in central European regions, e.g. Poland, parts of Germany and northern Italy, increased legume cultivation may give high yield benefits for cereals, while in much of Scandinavia and central Italy the benefits may be small. In southern Spain, the benefits are clear (Figure 3).

There are long-term economic effects that are not easily captured by gross-margin analysis. These arise from long-term yield increases, fertiliser savings, and reduced labour demand in peak periods in autumn due to replacing winter-sown with spring-sown crops. Most of these effects are not automatic but depend on farmers' management decisions as well as environmental and agronomic conditions, so they are difficult to quantify and to evaluate. Von Richthofen et al. (2006) evaluated pesticide savings worth up to 31 €/ha and reduced cultivation costs of up to 10 €/ha, which are included in Table 1.

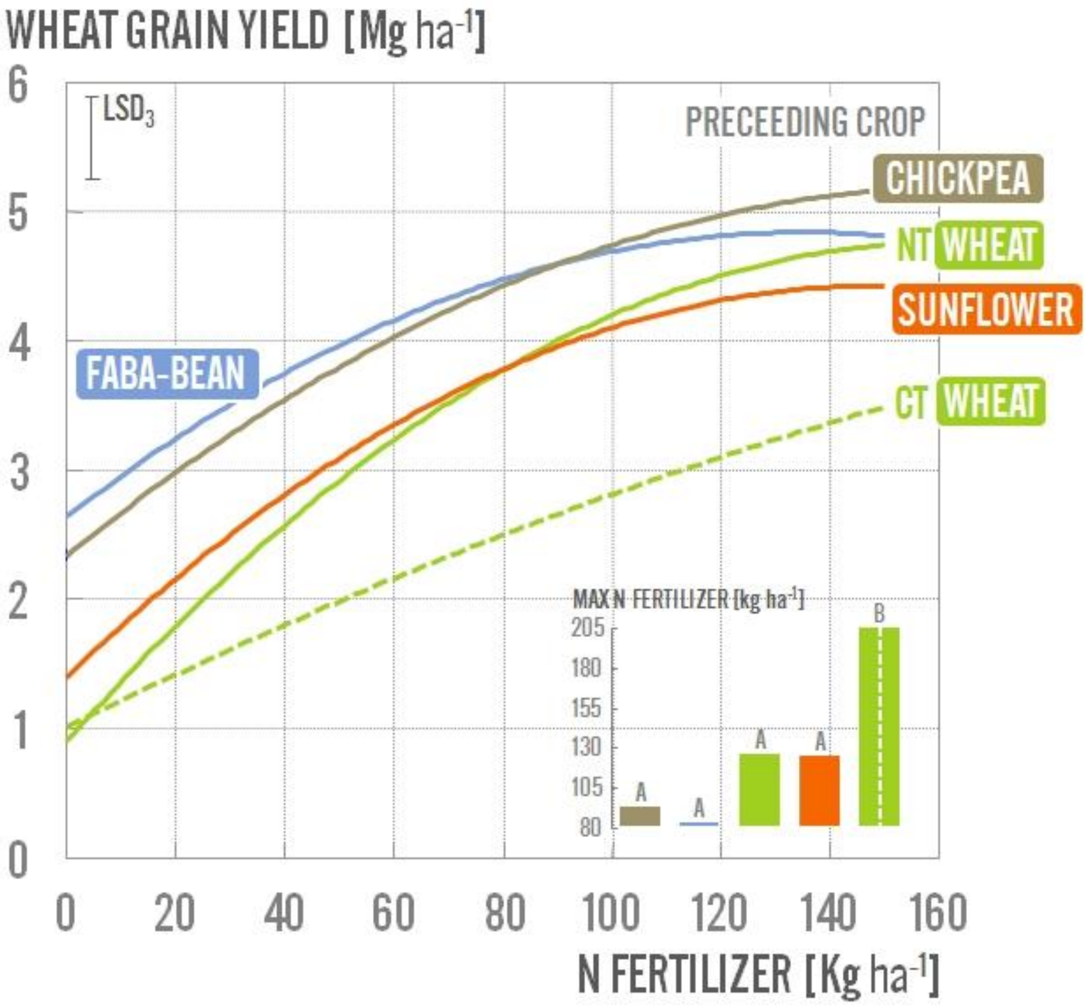

Figure 3. Tillage system × crop rotation × N fertiliser interaction effect on wheat grain yield in the long-term rotation trial at the University of Cordoba, Spain. All regressions were significant. For simplification, tillage systems and N fertilisation (single or splitting) within a crop rotation were not shown when there was no significant difference. The least significant difference 3 (LSD_3) is for comparison of different levels of tillage systems and crop rotation. For maximum fertiliser, means followed by the same letter are not significantly different at $P < 0.05$ according to LSD.

Table 1. Yield effects in Europe of grain legumes and rapeseed as pre-crops

Pre-crop	Subsequent crop	Yield effect		Country	Source
		(%)	(kg ha^{-1})		
Pea	Barley	13-62	671-1500	DK	Jensen et al. 2004
	Barley	15	799	DK	Jensen and Haahr, 1990
	Wheat	9	493	DK	Jensen and Haahr, 1990
	Wheat	-2	-147	DE	Kaul, 2004
	Wheat		583	DE, FR, ES, CH, DK	von Richthofen et al. 2006
	Rapeseed	10	580	CH	Charles and Vullioud, 2001
	Rapeseed	19	499	DK	Jensen and Haahr, 1990
	Rapeseed	54	1364	DE	Kaul, 2004
Faba bean	Wheat	3		FI	Keskitalo et al. 2012
	Wheat	62	2693	DE	Köpke, 1996
	Wheat	3	221	DE	Kaul, 2004
	Wheat		870	DE, FR, ES, CH, DK	von Richthofen et al. 2006
	Rapeseed	13	328	DE	Kaul, 2004
Lupins	Barley	15-77	774-1301	DK	Jensen et al. 2004
	Wheat	-12		FI	Keskitalo et al. 2012
	Wheat	-2	-147	DE	Kaul, 2004
	Rapeseed	23	581	DE	Kaul, 2004
Lucerne, clovers	Wheat	24-36	488-733	LT	Skuodiene and Nekrosiene, 2012
	Wheat	51	1994	SE	Wivstad et al. 1996
Rapeseed	Wheat	8-31	434-1374	DE	Köpke, 1997
	Wheat	2-13	130-694	HR	Kraljević et al. 2007
	Wheat	7		FR,AU	LMC International, 2009
	Wheat		550	DE, FR, ES, CH, DK	von Richthofen et al. 2006
Average grain legumes		15	671		
Range		-12 to 77	-147 to 2693		

Suppression of pests, disease and weeds, and its effect on pesticide applications
Since legumes are generally not susceptible to the same pests and diseases as the main cereal crops, they break the life-cycle of these diseases and pests, reducing their incidence in the following crop. This is particularly true of soil-borne root diseases such as take-all root rot (*Gaeumannomyces graminis*) of cereals (Kirkegaard et al. 2008). The process gives rise to the term 'break crop'. Root-lesion nematodes in the genus *Pratylenchus* are pests of a wide range of crops, and some cultivars of faba bean suppress the growth of *P. neglectus* (Yunusa and Rashid, 2007). Through improving root health, legumes can also benefit the N nutrition of the subsequent crops (Kirkegaard et al. 2008).

Nevertheless, legumes can also increase the incidence of some diseases (Skuodiene and Nekrosiene 2012). Broad-spectrum diseases such as *Sclerotinia sclerotiorum* and *Rhizoctonia solani* flourish on many legumes as well as on other broad-leaved crops, so a 3-4 year interval between successive legume crops is widely recommended.

Reduced pesticide use has a resource impact at the farm level and an environmental impact at agri-food system and global level. Reductions in overall pesticide use can be expected as a consequence of the break-crop effect. However, the use of pesticides in grain legumes should not be overlooked, as most broad-leaved break crops, including legumes, receive as much pesticide as mainstream cereals (Kirkegaard et al. 2008).

Economic analyses (von Richthofen et al. 2006) assumed that pesticide application in cereals grown after legumes can be reduced, leading to a 20-25% reduction in pesticide costs for the succeeding crop. Nevertheless, assessed over whole cropping sequences, the amount of pesticides used in sequences with and without grain legumes is about the same. The environmental impact depends on the specific pesticides used. In one out of four case studies (in Saxony-Anhalt, Germany), the terrestrial ecotoxicity potential was 7% lower for the rotation with grain legumes due to the reduction in use of problematic pesticides (von Richthofen et al. 2006).

NOVEL SYSTEM DESIGN

Geoff Squire and Pete Iannetta, JHI, UK

In real terms, the total average quantity of N needed in a temperate, cereal-based five-year crop sequence (without legumes), is around 750 kg ha^{-1} (or about 150 kg ha^{-1} $year^{-1}$). Of the options to reduce this level of synthetic N in the near term without decreasing yield, the only option is to increase the proportion of legumes within crop-sequence. A legume crop can fix up to 200 kg N ha^{-1} (or more), with up to 80 kg ha^{-1} left in field as crop residues, which is roughly half of the N requirement of a temperate cereal under standard cropping. The whole N requirement could be met under legume-based intercrops and catch-crops. However, whether the economic returns are lower or higher would depend on the efficiency with which legumes may be cultivated and value of the products in relation to their market demand and input costs. However, this considers only the commercial market forces, and we should also consider the extent to which legume-supported cropped systems maintain other important 'ecosystem services' (ES).

There are four categories of ES, and the incentives usually given to growers and landowners to introduce agri-environment schemes can generally be placed in the categories of '*regulating'* (*e.g.* control of soil erosion and reductions in emissions), and '*cultural*' (*e.g.* regional foods), as opposed to '*supporting*' (*e.g.* improving soil quality 'and' food webs', the basis of all other services), and '*provisioning*' (*e.g.* yield itself). The principle of our proposed novel system design guides us to begin by defining the key supporting and provisioning ES *then* proceed to particular interventions or cropping practices: not *vice versa*. This aspiration does not pre-empt the implementation of specific interventions or cropping practices (*e.g.* legume cropping), as long these are targeted towards achieving higher level ES attributes that move the system towards sustainability.

Therefore, we examined the use of a decision aid model (or '*tree*'), with supporting and provisioning ES as the '*highest-level attributes*' (*e.g.* maximising vegetable protein production and limiting loss of environmentally damage N), which are determined by '*high-level attributes*', such as '*ecological processes*' (*e.g.* the N cycle, minimising N_2O losses), which are in turn determined by specific '*lower level attributes*' such as '*life forms*' (*e.g.* crop types), and '*interventions*' (*e.g.* agricultural practices). The attributes at all levels should be defined by '*indicators*' which are measured in absolute (quantifiable) or categorical (qualitative) values (Figure 4). The costs of the interventions to achieve the highest level attributes could also be calculated and would feed into other parts of the tree, for example that dealing with gross margins.

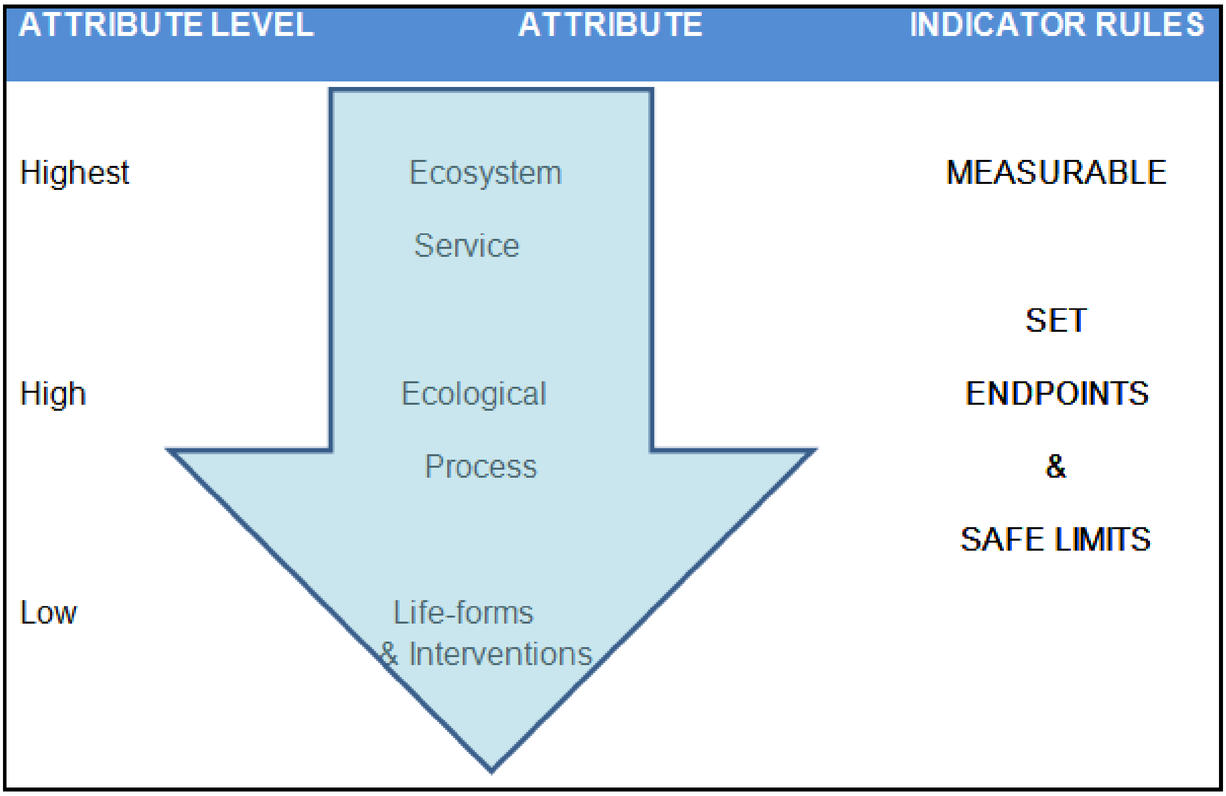

Figure 4. A schematic diagram highlighting the principles and elements which underpin the proposed novel system design tool. Namely that the design process occurs in the direction of the yellow arrow: i.e. only after first specifying the highest level attribute (a specific ecosystem service), and to assess this before and after intervention according to the suite of indicators chosen.

A systematic and comprehensive approach must therefore be applied to the use of indicators in field trials in order to attain a true (and not relative), measure of system state, and before *and* after interventions. Furthermore, indicators should be robust at the point of estimate, and of a form in which a higher level attribute can be split into two or more, lower level attributes. Robust estimation and integration of indicators along the chain (in Figure 4) ensures that the most important attributes are considered and those of no great consequence do not have undue influence.

We may aspire to achieving several different, and even conflicting, highest-level attributes, simultaneously by manipulating the suite of lower level attributes and this complexity may be facilitated by a 'Multi Attribute Decision-aid Model' or MADM. Effective use of a MADM demands that the highest-level ES attributes should be defined by specific '*assessment endpoints*' for key ecological and economic indicators that should be managed so they remain within '*safe limits'* (Figure 4). The MADM developed in this project is facilitated by a DEXi decision tree, but the principles of design come first: the structure of the DEXi programme simply facilitates the design.

However, several challenges are faced in using MADM for novel legume-supported system design, as information is lacking on some of the ecosystem services, processes, life forms and interventions that are necessary to render the decision aid predictive. It is also a reality that the safe limits for an ecological process may not be available and may differ between production systems, depending on context. For practical purposes, the key indictors should be easily measurable. While the indicators for some areas of the tree would be routinely measured in many assessments, notably those in the compartment for provisioning services, in contrast a full set of indicators for supporting services are less likely to be measured in a standard field trial. This uncertainty is compounded by a further level of complexity, '*scale*'. Having identified a highest level attributes, it is necessary that the system-designer identifies the scale at which the attribute is satisfied, and the scale (or scales) at which the effective interventions may be implemented. Scales tend to be defined at patch, field, farm, landscape, regional, national and even global levels. For crop production, most provisioning and supporting services can be generated and satisfied within the production unit (field scale). However, most regulating services are satisfied by interaction between several units before they can be satisfied. For example, the control of farmland pests cannot be satisfied adequately by interventions carried out only by production units (farm scale) in isolation. Therefore, when using and testing the MADM, comparison of the scenarios across scales is also necessary. Where deficiencies exist, it is still be possible to work through the process of design by setting semi-quantitative or qualitative endpoints or even uncomfortable generalisations; and it is currently necessary that a 'bank' of measured or modeled attributes is established for used in different parts of the tree as necessary.

Many of the indicators that should be used to compare different legumes or cropping systems with and without legumes have been captured in the MADM we present, and on the whole these are standard well-established measures which are used routinely in agronomic field work and in ecological studies of farmland. However, of the more complex measures, such as those which relate to nodulation, N fixation, the N residues they leave for the next crops and losses as part of the N cycle would seem to be essential for the design of legume based systems: yet there is negligible information for these attributes in anything but highly controlled conditions. It was therefore very soon realised that current system design tool may have to proceed in the absence of this important information and with specified assumptions we must defined the state of important ecological processes in semi-quantitative terms (such as large, medium small), or values may be estimated from experience in other countries. For example, on nitrogen fixation, there is strong evidence that legume crops are capable of providing all their own N-requirements through BNF (*ca.* 200 kg N ha^{-1}), and that some of this N can also be made available to succeeding (or accompanying) non-legume crops. Moreover, effective interventions should encourage management practices that help bring about low soil N status, in order to maximise BNF at the field/farm scale *and* 'participatory practices' at the level of the catchment.

Stakeholders' perspectives

A meeting of a group of stakeholders organised by the JHI agreed that legumes supported cropped systems represent a sensible basis upon which they may realise and balance the goals of environment- and food-security and to increase Europe's capacity for vegetable protein production. Critically, it was also acknowledged that the benefits of legumes are multi-functional, spanning a wide range of ecosystems services and encourage resource use efficiency and exploiting the natural chemical cycles. As such cropped legumes offer a solution to societal challenges in the environmental, agriculture and public-health arenas. It was also acknowledged on economic grounds and even with current legume varieties where they are cultivated well, that legume supported cropped systems are more profitable that systems which are not legume supported. The understanding, that legumes should play central role for in the generation of profitable food secure systems is also justified from many other sources, and not least among PROFETAS (http://www.profetas.nl/), and Aiking et al. (2011). However, to ensure that this potential is realised consistently, it was also recognised that six key aims have been identified:

- The underpinning retail-market demand of legume-based products must be increased, and with specific reference to grain legumes and that this demand is stable and sufficiently large to justify the second criteria, which is that;
- The underpinning capacity and infrastructure of businesses in the food processing sector must be developed to process the legume based commodities to the necessary qualities and/or grade; and for the various food and feed technologists who manufacture legume based products for retailers;
- There is a need to develop a broad range of legume-based products as human food staples for countries in Europe (e.g. grain legume-based breads and ready meal ingredients). This would support a market value which of higher value than their main current market which is for animal (excluding aquaculture) feeds;
- There is a need to initiate a strategic educational and marketing strategy which is tailored of the various stakeholders, and especially the public, to encourage the evolution and success of the legume supported agri-food web: since it is only through such concerted action that the aims raised above may be realised successfully. This would likely be returned in real cost savings through

improved business efficiency, developing new markets and lower public health costs. Major investment in initiatives should be specifically targeted.

- The public, including efforts mediated though schools, need to motivate new behaviours with respect to food culture and a better balance between meat-based and vegetable protein based dietary patterns and; growers *via* agriculture-advisory and extension services need to ensure growers are using the best practices for their legume supported crop system legume production and research. This should extend to establishing recognised 'centres of excellence' for this purpose.
- There is a need to develop IPM strategies for legume supported crop systems, since there is a critical lack of capacity in this regard. Legumes could occupy a 50% inclusion rate within the rotation (as an equal balance of forage and grain legumes to maximise BNF and productivity whilst minimising soil surface N balance and inorganic N use but it should be anticipated that under current conventional practices the consequent legume disease pressure would increase.

Across all stakeholders there is a clear distinction in the level of concern that was directed towards forage and grain legumes. The trait improvements seen as necessary for legumes cultivated as forages are limited to functional diversity, nutritional quality and agronomy. That is, forages have received no special attention for development as understory species to enable inorganic fertiliser-free non-legume (grain) crop production: and despite evidence that this is possible. The uptake of legume-supported systems will only be optimised if forage legume types are also developed specifically for their utility as understory-intercrops to support non-legume grain crop production. This intervention may also present an effective addition to IPM strategies.

It was the view of the stakeholder group that research funders should ensure that future development of the legume-supported agri-food web may be supported effectively by a focus upon the following areas, and in priority order:

1. Supporting the development of a decision support tools to enable more informed choices by legume growers that will help them deliver positive economic effects over the long term. This decision support tool should developed upon the 'principles of novel system design', defined in this report.
2. Identifying the barriers and opportunities for uptake of legume-based food within the human food-chain and on that knowledge foundation:
3. Increasing the knowledge base of legume nutrition and food-chemistry to help developing legume-based products as staple food stuffs for humans within European society, and feeds for lifestock, including aquaculture production;

4. Quantifying the human health and socio-economic impacts of greater consumption of legume based foods, while current data does indicate several health benefits if legume protein consumption, the socio-economics benefits from large scale adoption remain to be gauged.

Principles guiding the design of novel systems

Legume crop breeding investment must extend beyond improving traits which are of direct agronomic interest (such as yield, earliness and disease resistance), to attributes which underpin ecosystem services, especially provisioning and supporting services (as outlined in the principles of ecosystem design, above), but also cultural and human health provisions. For example, nutritional attributes whether quantitative (amount of protein) or qualitative (*e.g.* higher essential amino acid composition), and to ensure that crops present sufficient levels of diversity to cope with the biotic and abiotic stresses, and especially in response to the inevitable climate change scenarios (see below).

Legume crop types used should also be developed in concert with the isolation of compatible 'elite rhizobial isolates', which may enhance biological nitrogen fixation. Within European agriculture and research, there are few studies which relate the quantification of biological nitrogen fixation using robust methodology with genetic characterisation of the plant *and* rhizobial symbionts which underpin this capacity. Thus, biological nitrogen fixation is often considered as an *ex gratia* benefit and the possibility that there may be inadequacy in it is often denied by farmers and scientists alike. However, the success of legume supported agricultural economies such as Brazil and Australia, has been determined by the provision of elite rhizobial isolates for specific soil environments, and also best-fit-for-purpose plant types. This approach has not been tested and applied systematically in Europe, and it has not been explored at all with respect to intercropped systems. Such considerations become all the more pertinent when instability in grain legumes yields is usually considered to be a consequence only crop type.

With respect to forage legumes there is a need to develop nutritional attributes to maximise protein use efficiency, meat and milk quality (reduced the saturated fat content of meat and milk), though reduce biohydrogenation of fatty acids in the rumen (Luscher, 2014). Such improvements should extend to the breeding and development of legumes, and associated non-legume crop types, for intercropping-supported systems. Especially since sustainable intensification is unlikely to be achieved without a significant increase in the 'land equivalent ratio' that can only be bourn within minimum inorganic inputs from legume based intercropping. This breeding effort should be carried out in and for the environment in which deployment is intended. The same may be said for associated cereal types, which have been bred for high performance as sole crops using inorganic nitrogen provision; not intercropped legume-supported systems that rely on renewable nutrient cycling. Similarly, and as already highlighted above, forage legume understories have been bred primarily for production of biomass for animals, they have not been developed as understory (intercrop specific) types to support the production of non-legume grains (without inorganic fertiliser addition). They also haven't been bred to take account of non-crop diversity by provisions to pollinators, crop pest predators and parasitoids. These issues underpin strategies for IPM and that support soil fertility building, natural chemical cycling and renewable nutrient use.

It may be expected that climate change mitigation and adaptation strategies will involve greater resource use efficiency, halting deforestation and crucially reserving agricultural land for food production. Agroecosystems will have to become more diverse than they are currently (Foley, 2011). For example, intercropping crop mixtures that are genetically and functional diverse at intraspecific as well as the interspecific levels. These would need deployed within low- or even no external-input ('renewable nutrient' based), systems that also utilise wild and perennial species in non-cropped *and* cropped areas. It is also likely that this development would also present the opportunity to wisely deploy perennial nitrogen fixing (leguminous or actinorhizal), shrubs and trees. Such interventions at the level of the farmed unit (field and farm scale), should be integrated with strategies at the landscape scale.

AGRO-ECONOMIC ANALYSIS OF CROPPING STRATEGIES

Peter Zander, ZALF, Germany

While it is well known that legume crops have many positive environmental effects in rotations, further knowledge is required to support their incorporation into arable and forage rotations and assessing the financial risks and benefits of doing so. Hence, this project developed a modeling approach to systematically generate and assess rotations with and without legumes for five case regions across the Legume Futures network (Reckling et al. 2013). A crop rotation generator produced agronomically sound rotations based on expert derived crop rotation restrictions. The assessment included nitrogen fluxes (NO_3^--N leaching, N_2O emission, N-balance) gross margins, pest, disease and weed infestation risks. Experienced agronomists at each of the five partner institutions (NARDI, SLU, SRUC, UDM and ZALF) evaluated the agro-economic potential of the generated rotations and the feasibility of their application.

The outputs of the rotation generation were provided to the agronomists in spreadsheets, with one line per rotation (up to 22,000) and separate sheets for arable ± legumes and forage ± legumes. The agronomists were asked to assess the most profitable rotations ± legumes and their environmental impacts as produced by the model, and to consider the likelihood of adoption of the different rotations. Three of the sites (Eastern Scotland (UK), Calabria (IT) and Brandenburg (DE)) covered more than one type of environment, and one site (Sud-Muntena (RO)) had no forage options.

In five out of eight cases, legume-supported arable rotations identified were estimated to be more profitable than the corresponding non-legume rotation (Table 2), and in three of four cases, the legume-supported forage rotation was more profitable than its legume-free equivalent. Therefore at current estimates of crop values and input costs, it is already worth including legumes in rotations in many European conditions. The legume sometimes appeared as an additional year in the rotation and sometimes as a replacement for another crop. Radically different rotations at each site were generally much less profitable. The core crops of the rotations varied with location and soil type.

In the process, the agronomists noticed some peculiarities in their rotations, showing that further iterations of the process were necessary to optimise the outcomes. The first round of generation for Eastern Scotland put potato into every rotation, but this is not appropriate where there are steep slopes, so potato-free rotations were also generated.

The gross margins were high when high-value crops such as potato, linseed and common bean were included, but since these markets are often specialist, alternative rotations were also inspected. In Sweden, replacing linseed, a high-value food and ingredient crop, with faba bean, resulted in loss of profit. In Brandenburg, the rotation with pea was 5 years instead of the 3-year without a legume, but profitability was still low (Schläfke et al. 2014). Including legumes in the rotations decreased nitrate-N leaching potential in three systems, with the largest reduction in eastern Scotland without potato, and increased it in another three, with the largest increase in irrigated highlands of Calabria. Potential N_2O emissions were reduced in all eight arable systems.

Table 2. Most profitable arable rotations with and without legumes at each of the five test sites, including annual gross margins, nitrate-N leaching potentials and nitrous oxide emission potentials. Differences in the rotation are highlighted in bold.

Region ± legume		Most profitable rotation	Gross margin (€ ha^{-1})	NO_3^--N leaching (kg ha^{-1})	N_2O emission (kg ha^{-1})
Sud-Muntena, Romania	-	Maize / W Wheat / W Rape	432	13	3.5
	+	Maize / W Wheat / W Rape / **Common Bean**	850	11	2.8
	+	Maize / W Wheat / W Rape / **Soybean**	518	14	2.8
Eastern Scotland, UK + potato	-	Potato / W Wheat / W Oat / Swede / **S barley** / **W oat**	844	41	5.3
	+	Potato / W Wheat / W Oat / Swede / **S Wheat** / **Faba Bean**	889	41	5.2
Eastern Scotland, UK - potato	-	W Rape / W barley / W Oat / **S Barley** / W Barley	490	46	5.2
	+	W Rape / W barley / W Oat / **Faba Bean** / W barley	547	36	4.6
Calabria, Italy, irrigated highland	-	Potato / W Rape / W Wheat / **W Rape** / **W Wheat**	549	61	2.4
	+	Potato / **Lupin** / W Rape / **Lupin** / W Wheat	709	81	2.1
Calabria, Italy, rainfed	-	W Rape / W Wheat / W Rape / W Wheat	267	12	2.0
	+	W Rape / W Wheat / W Rape / W Wheat / **Faba Bean**	233	14	1.6
Västra Götaland, Sweden	-	W Rape / W Wheat / **linseed** / W Wheat / S Barley	644	34	3.7
	+	W Rape / W Wheat / **faba bean** / W Wheat / S Barley	593	34	2.4
Brandenburg, Germany	-	W Rape / W Wheat / **S Barley**	130	28	4.7
	+	W Rape / W Wheat / W Rye / W Rye / Pea	111	20	3.5

S = Spring, W = Winter

The generator provided novel rotations that were often unexpected by the local experts, and tested the economics as well as many aspects of the agronomic and environmental impact. The gross margin calculations are sensitive to market-based price fluctuations, and the development of new, high-value uses for any of the crops, or major changes in their yields, will change the outcomes. The environmental impacts depend partly on such features as rainfall distribution leading to saturation of the soil, and while these vary from year to year and may change gradually as climate changes, the relative impacts of the different crop species are likely to remain consistent.

CASE STUDIES

Fred Stoddard, University of Helsinki, Finland

One of the first objectives of Legume Futures was to conduct a set of case studies across Europe on established field experiments. In addition to providing data for the environmental and economic assessments, these 'case studies' were to inform and validate new cropping system designs and provide a focal point for the local development of new cropping systems. In this way, the project could fulfil the European Commission's request that, on the basis of case studies, the project should take full consideration of the variety of agro-economic and pedo-climatic situations in Europe.

A case study is a research approach commonly used in social science that seeks to identify underlying principles by investigating a single individual, group or event (the case) in-depth. It is based on empirical inquiry that investigates a phenomenon within its real-life context. Case study research can include quantitative evidence, rely on multiple sources of evidence, and can benefit from the prior development of theoretical propositions. Therefore, the European Commission's use of the term 'case study' highlighted the role that local and regional expertise and associated qualitative evidence should provide in this research.

The consortium's 18 experimental field sites were the primary source of quantitative information for the case studies (Stoddard *et al.* 2013a). This report provides an overview of the experiments used and reports on insights that the partners have gained from their experimentation and related activities. The case studies thus include knowledge from experiments in the context of the regional agricultural systems where the experiment is located.

There was consensus in the Legume Futures consortium that increasing legume cultivation (by area or increasing legume share in rotations) would contribute to greater protein self-sufficiency for Europe and reduce independence on imported protein.

Throughout the geographic regions, limitations to the usage of grain legumes were seen as broadly similar. Climate constrains the choice of species and cultivars in all regions, with earliness of maturity being an important trait for the boreal and oceanic zones, and escape from terminal drought important in the Mediterranean zone. The lack of recent investment in breeding throughout Europe means that there have been few advances in breeding for disease resistance in grain or forage legumes. Some users of legumes grow them in rotations that are too short, leading to the build-up of soil-borne pathogenic fungi (the best known case being *Aphanomyces* root rot of pea in France) that result in poor emergence and vigour.

Further limitations come from farmers' unfamiliarity (particularly younger farmers) as cereal monoculture has become more widespread in Europe. The small batches arising from the relatively small scale of production limit markets (compared with soya bean meal which is uniform). Legume Futures partners also reported considerable prejudice (legumes are "demanding" crops that give "unstable" yields and "low" profits so they are "for the organic sector only"). A Finnish farmer said "I don't have time to wait for legume nitrogen" and an Italian farmer said that "legumes are for old men", and these statements lodged in the memories of our correspondents. The environmental effects of legume crops have not been economically evaluated and since they are public goods, there may not be an appropriate evaluation.

Markets are limited by several factors. First is the wide range of species that can be grown for stockfeed or animal feed ingredient use, thus by definition providing a wide range of qualities in contrast to the consistent uniformity of soya bean and its meal. Furthermore, anti-nutritional factors differ between species and this variation limits their use in feed compounding. Breeding is needed to improve feed quality (e.g., low vicine-convicine faba bean) and to improve stress tolerance (against drought, pathogens, and extreme temperatures). However, the market price of locally produced legume products is competitive compared with imported soya bean products.

Much information from partners that was particularly relevant to specific regions relates to the range of crops adapted within the case region and the specific biotic and abiotic stresses that affect them in those regions. In the Continental region, where sowing is mainly in the spring, lupins are important in Poland and soya is important in Romania, while almost all grain legume species are used in one part or another of Germany. In the Mediterranean region, broomrape (a parasitic weed of legumes) and terminal drought are far more important stresses than elsewhere.

Every case study mentioned the potential of at least one grain or forage legume species that was even more underutilised than the mainstream species. Serradella could return to the rotations in Poland, while lentil could be used in many countries, as shown by its success in the nemoral climate of Saskatchewan in Canada.

Even though we as scientists feel that the message about the positive impacts of legumes on crop rotations and the environment is well known, most of the correspondents in the consortium felt that farmers in their regions did not adequately understand these effects, and management knowhow is lost as the more experienced farmers retire. More novel methods such as intercropping have made little impact at the farm scale, because farmers do not know how to manage these crops, except in the narrow case of cereal-legume mixtures for on-farm livestock feeding in organic systems.

We may expect that increasing knowledge of the environmental benefits of legumes in rotations, and of their dietary benefits to the consumer, will increase their usage in cropping systems. Interest in legume production will also continue to follow increases in price of soya bean and N fertiliser. As novel food uses are developed, market demand may be expected to increase. The research knowledge on the potential of legumes has to be transferred to farmers and show the best practices to manage/establish legume based agriculture, as well as to develop legume processing and fractionation facilities.

However, at the individual crop level, the economic return from grain legumes is usually lower than other crops. In many situations, growers need appropriate external financial support to justify the introduction of legumes into their systems. An example of an appropriate measure is The Rural Environmental Protection Scheme (REPS), implemented by the Irish Department of Agriculture, which financially rewarded farmers for farming under "environmentally friendly" practices. Several of our contributors were concerned about the draft “greening” revisions of the Common Agricultural Policy (CAP) and whether it would adequately promote crop rotations.

Policies should seek to support agronomic and environmental outcomes. Local and international policy makers need to be informed on the role of legume in sustainable agriculture and on their potential benefit to the environment. The social and environmental effects of soya bean production in South America should also take in account when decisions are made.

Atlantic region

This region is characterised by mild winters and plentiful rainfall distributed through the year. Autumn-sown crops take priority over spring-sown, and the yields of small-grained cereals are among the highest in the world, showing a substantial yield difference from those of the grain legumes. The main grain legumes are pea and faba bean, with much of the latter being autumn-sown, particularly in England. The primary forage legumes are white clover. Our participants are in Scotland and Ireland, and the region spreads well into France, the Netherlands, and north-western Iberia.

Continental region

The range of crops is probably widest in the Continental region, where winters are shorter and less harsh than in the Boreal-Nemoral region, and rainfall is less limiting than in the Mediterranean region. Lupins are well adapted to these conditions. The margin between cereal yields and those of broad-leafed crops is less than in the Oceanic region, but is still large. Except in Poland where lupins are the main grain legume group, grain legume production is based on faba bean and peas (Figure 6). Soya bean, common bean and other warm-climate crops are also grown, particularly in the southern part of the region. Forage legumes include lucerne along with the clovers, and many others such as serradella are grown on a small scale. Autumn-sown grain legumes succeed only on the margins of this region. Our case studies from this region are from Germany, Poland and Romania.

Mediterranean region

This region is characterised by winter rainfall and summer drought. Grain legumes are primarily autumn-sown and mature in the spring. Where irrigation is possible, warm-season legumes can be grown, as is the case at our Greek partner organisation. Irrigated maize leads the yield of all grain crops and the margin between wheat yields and legume yields is relatively small (Figure 7). Traditional food uses of grain legumes in this region maintain the economic viability of these crops much more than in the other three regions. This is the only region with a significant area of chickpea, which is primarily a food crop.

Forage legumes, in contrast, are relatively little used, again with the exception that irrigated lucerne can produce remarkably high yields and maintain its productivity through several harvests per year. Our correspondents cover the breadth of the region from Spain through southern Italy to Greece.

Boreal-nemoral region

This region is characterised by short summers with very long days, and long winters. The range of crop species and cultivars is narrower than in the other regions and crop yields are generally lower than further south, because of the short growing season. The main grain legumes are pea and faba bean and the main forage legume is red clover. Our correspondents are in Finland, Sweden and Denmark, and the region includes the Baltic countries. The Danish sites are at the junction of the Boreal-Nemoral, Continental and Atlantic regions, but still have much in common with the Boreal-Nemoral region except for the possibility of more numerous harvests of grass-legume forages during the summer.

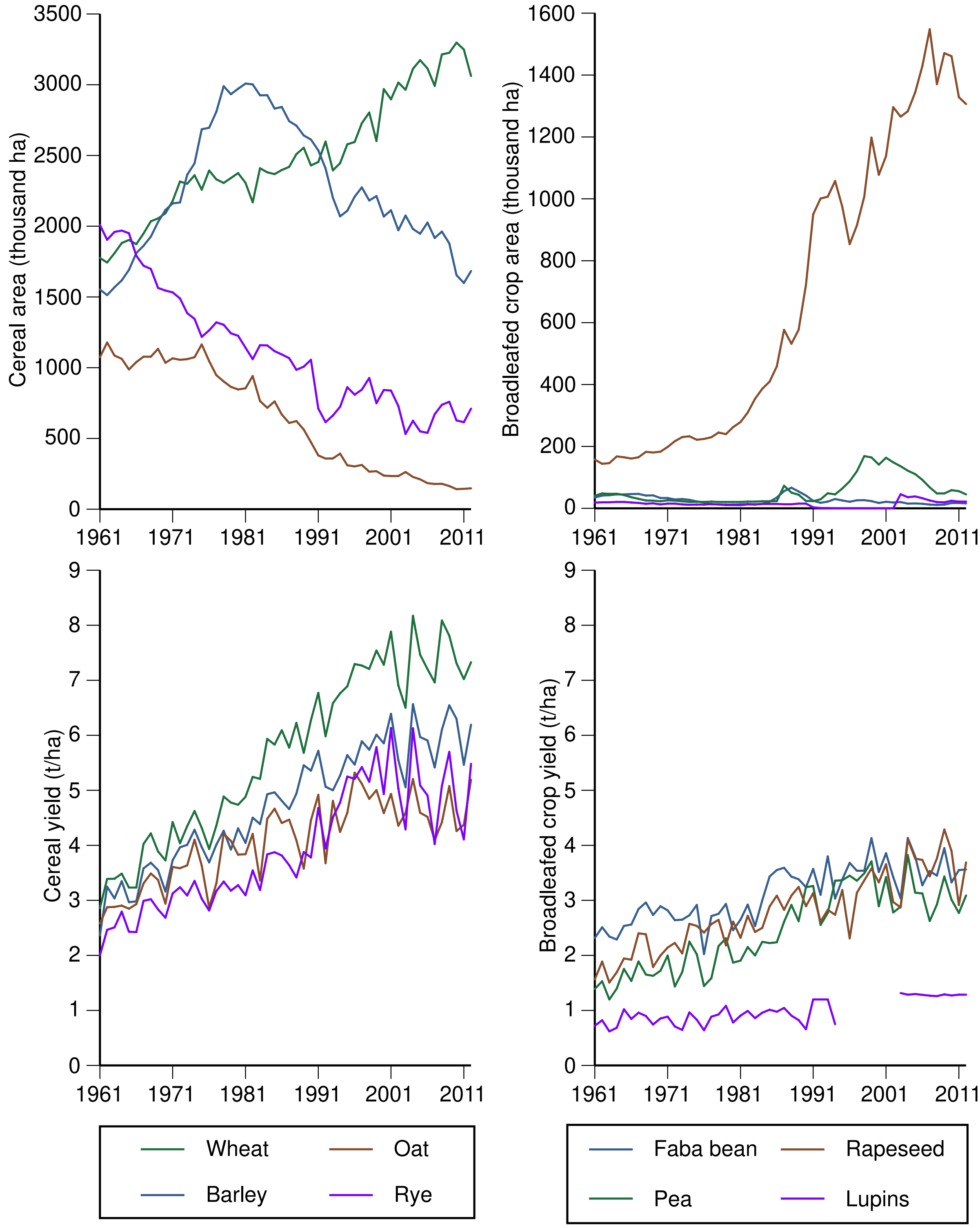

Figure 5. Harvested areas (thousand ha) and average yields (t/ha) of the main cereals, grain legumes and oilseeds in Germany, 1961-2012 (FAOstat data).

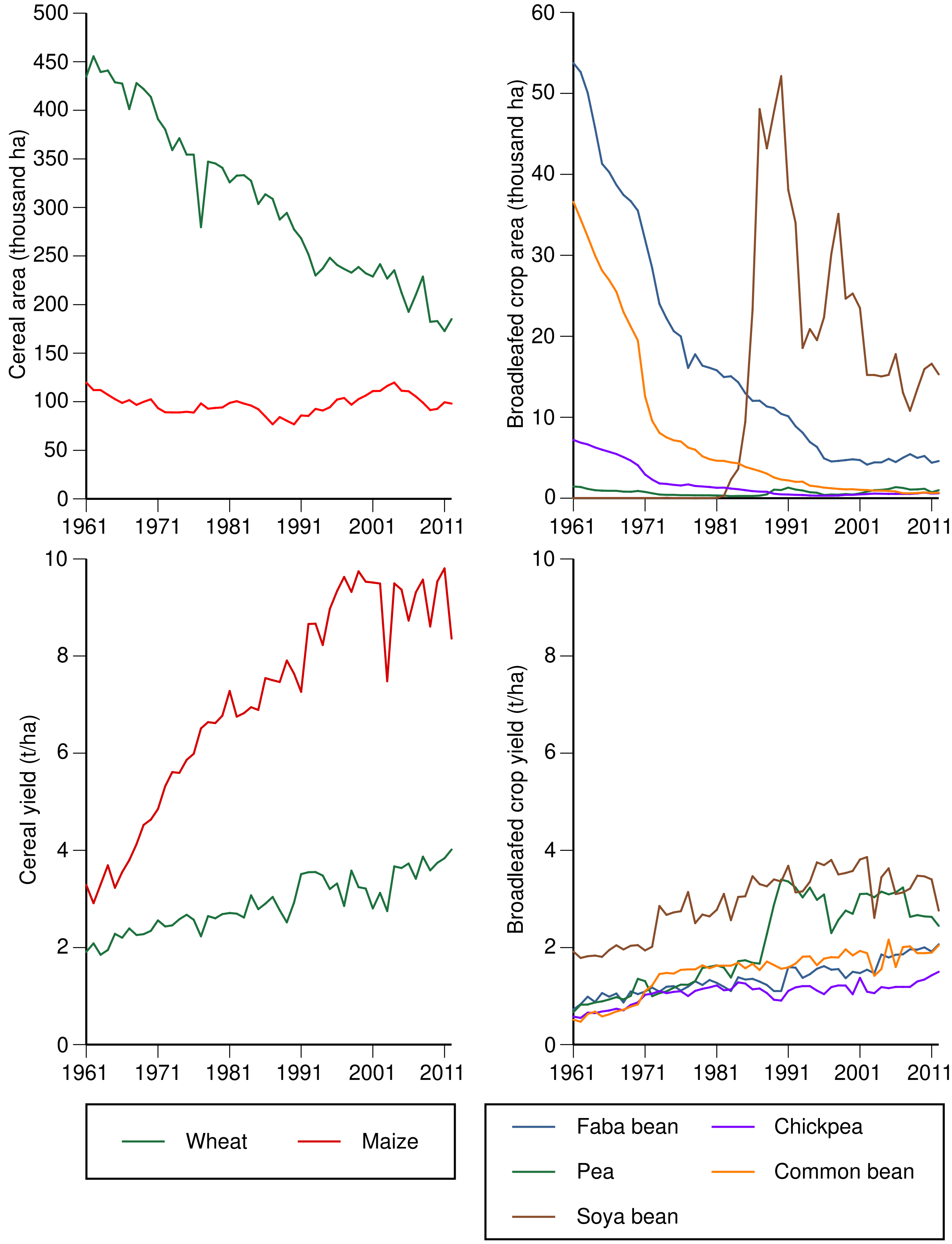

Figure 6. Harvested areas (thousand ha) and average yields (t/ha) of the main cereals, grain legumes and oilseeds in Italy, 1961-2012 (FAOstat data).

NON-TRADITIONAL USES OF LEGUMES IN NOVEL FEEDS AND INDUSTRY

Fred Stoddard, University of Helsinki, Finland

The high protein concentration in legumes makes them suitable for a range of foods and feeds and also affects their use for other industrial purposes. Biological nitrogen fixation is a characteristic of pioneer plants, allowing them to remediate soils otherwise unsuitable for agriculture. Legumes have evolved many biochemical mechanisms that protect them from herbivores, and the bioactivity of these compounds makes them suitable for many non-food purposes. Hence the project reviewed a range of non-traditional uses of legumes (Stoddard et al. 2013b).

Novel uses in animal feed

Grain legumes may be ensiled in much the same way as forage legumes, and there are reports on the use of pea, faba bean, and all three agricultural lupins in this way. They contain little water-soluble carbohydrate and have a high buffering capacity, so ensiling them generally requires wilting, treatment with additives such as formic acid or lactic acid bacteria (Pursiainen and Tuori, 2008), or mixing with a cereal (Mariotti et al. 2012).

The presence of bioactive chemicals in grain legumes affects their usage for monogastrics more than that for ruminants. The breeding of faba bean cultivars low in vicine-convicine has allowed this crop to be used for laying hens and broilers, both of which are sensitive to these compounds (Vilarino et al. 2009). The low digestibility of the storage galactan in lupin seeds reduces their value in monogastric feeds, but supplementing the feed with appropriate glycanases improved broiler performance (Steenfeldt et al. 2003). The standard ileal digestibility of protein from narrow-leafed and yellow lupin was as good as that of soya bean meal, whereas those of pea and faba bean were somewhat lower (Jezierny et al. 2011), showing the potential for use of these crops to replace imported proteins.

Uses for fish and crustaceans

Other sources of protein and oil can substitute for the fish products normally used for feeding many farmed fish and crustaceans (Trushinski et al. 2006) and herbivorous fish such as carp can by definition use plant-based feeds. Soya bean meal had a negative and dose-dependent effect on salmonid fish digestive systems attributed to various anti-nutritional factors (Krogdahl et al. 2003). Faba bean meal and narrow-leafed lupin meal generally outperform soya bean meal in diets for this class of fish, and blending of protein sources avoids many problems (Gomes et al. 1995). Narrow-leafed lupin meal can be used at up to 30% of the diet of rainbow trout (*Oncorhynchus mykiss*) (Glencross et al. 2008) and the protein concentrates from this species are efficiently converted by the fish (Zhang et al. 2012). Similarly, Pacific white shrimp (*Litopenaeus vannamei*) grew well with up to 50% of the protein in the feed being plant-derived (specifically, from Andean lupin). The presence of some starch helps the formation of feed pellets under heat extrusion, so faba bean or pea flour can replace some of the wheat or other cereal starch in the formulation.

Bioenergy uses

The nitrogen-fixation capacity of soya bean gave it a significant advantage over other oilseeds in a life-cycle analysis (Hill et al. 2006), but still is in the philosophically questionable area of using food materials for energy production. The oilseed legume tree *Millettia pinnata*, native to India, is suited to warm-temperate to semi-arid zones and yields similar amounts of oil per hectare as soya bean (Scott et al. 2008). By-products include a potential insecticide, karanjin (Vismaya et al. 2010), and an oil-free meal that can be used either in a methane digester or directly as an N-rich fertiliser.

Legume trees of genera *Acacia* and *Robinia*, with their nitrogen autonomy, have shown superiority to other rapid-growing trees such as *Eucalyptus* species and hybrid poplar in live-cycle analyses of cellulosic ethanol production in Spain, Italy and Greece (Gonzalez-Garcia et al. 2012, Tzanakakis et al. 2012).

Perennial grasses are also favoured for bioenergy production, and the potential for providing them with nitrogen by growing them in pasture-like mixtures with legumes has been tested in many environments. Results have generally been fairly neutral, with yield deficits more common than yield benefits (Butler et al. 2013) and the yield deficit greatly exceeded the value of the benefit from reduced GHG releases in the absence of fertiliser use (Epie et al. in preparation). A narrowly defined study based on energy and exergy relationships suggested that legumes have no merit in energy crop production, owing to their lower yields, but its authors acknowledged that environmental impacts were not considered, and the only legumes considered among the 12 bioenergy crops were lucerne and soya bean (Brehmer et al. 2008).

Biorefining

The concept underlying biorefining is that crop materials can be separated and used for several purposes, instead of a single use plus a waste fraction. Forage legumes or grass-legume mixtures may be refined to a protein-rich feed fraction from leaves and a cellulosic bioenergy fraction from stems (Thomsen and Hauggaard-Nielsen, 2008, Gonzalez-Garcia et al. 2012). Oil can be extracted from seeds of industrial legumes such as gum-arabic *Acacia* species (Nehdi et al. 2012) or *Robinia*, the oil-free residue can be used for methane generation, and the final digestate used as N fertiliser.

Phytoremediation

The nitrogen autonomy of legumes helps them to survive in some kinds of contaminated soils, and their root physiology helps them to cope with other mineral toxicities. *Galega orientalis* with its attendant *Rhizobium galegae* hastened the degradation of fuel oil from contaminated soil in controlled environments (Lindström et al. 2003) and supported a different microbiological community in the first year of a field experiment (Yan, 2012). A grass-lucerne intercrop promoted the degradation of polycyclic aromatic hydrocarbons (PAH) more than either of its component crops (Sun et al. 2011). Some heavy metals are excluded by roots of white lupin (Manninen-Egilmez et al. 2009) and tolerance to heavy metal contamination has been found in rhizobia (Nonnoi et al. 2012). The crops grown in these situations may not be suitable for food or feed, if they are contaminated with the PAH or heavy metal, but can be used for bioenergy or other biomass purposes.

Bioactive compounds from legumes

Legumes protect themselves from oxidative stresses and herbivores with a range of secondary compounds, including alkaloids, saponins and isoflavonoids, that have found antibiotic and health-promotive uses. In some cases the bioactivity has been attributed to specific compounds, but often only to a crude extract. Legume Futures report 1.3 provided a table of antibacterial, antifungal, anti-hypertensive, anti-inflammatory, anti-helminthic, anti-oxidant, anti-protozoan, anti-tumor, antiviral, herbicidal, insect-repellent, and insecticidal properties, and also teratogenic and neurotoxic effects, that had been identified in specific legumes since a review by Morris in 2003. Three genera that have received particularly deep attention are *Glycyrrhiza*, *Astragalus* and *Pueraria*.

Crotalaria species produce pyrrolizidine alkaloids that have been investigated by Legume Futures partner Lajudie at CIRAD in France. The alkaloids have effects on root-knot, root-lesion and other nematodes, reducing or eliminating these pests, often by stopping larval development (Subramaniyan and Vadivelu, 1990). The root-knot nematode *Meloidogyne incognita* is a major problem in tunnel-houses and other protected culture in the Mediterranean basin. Extracts of green tissues of crotalaria suppressed nematode growth (Jourand et al. 2004) and during the progress of Legume Futures, crotalaria was found to greatly reduce nematode damage to following lettuce and tomato crops in several experiments in three countries. Clearly there is potential to use crotalaria as a combined nitrogen-fixing and cleaning crop.

IMPACTS ON BIODIVERSITY

Susannah Cass, Trinity College Dublin, Ireland

The environmental impacts associated with the use of legume in crop rotations relate to a range of ecosystem services that are critical to any evaluation of the role of legumes in farming systems. In this section we report on the impact on biodiversity, nitrous oxide emissions, carbon cycling and land use change.

Legume supported cropping systems have the potential to influence biodiversity and the provision of ecosystem services in agricultural systems. Previous research has shown that management, in terms of tillage and agrochemical use, is the main determinant of biodiversity in legume-supported cropping systems, as they are in other cropping systems (Cass et al. 2014). In addition, legume biomass tends to increase the potential carrying capacity for associated biodiversity. However, the effects of legume cropping on biodiversity have shown to be complex, and to vary according to the species of legume introduced and the reason for its use (to reduce populations of certain organisms or to promote associated biodiversity).

In the Legumes Futures project, biodiversity associated with legume-supported cropping systems was assessed in ten cropping types in eleven established field sites, in eight European countries (Table 3). Three trophic groups were considered: primary producers (vegetation communities); decomposers (earthworms); and secondary consumers (predatory ground-dwelling invertebrates). Plant species were surveyed in a total of 2,164 1x1m quadrats in all 11 field sites; earthworms were sampled from a total of 860 standard-size soil blocks at eight field sites; and ground invertebrates were sampled in a total of 832 pitfall traps at three field sites. Additionally, soil faunal activity was measured at three sites. Samples were identified to species and analysed to determine patterns in species richness, diversity and abundance, and community composition, according to cropping system.

Table 3. Cropping Categories analysed. Crop categories 0-6 represent legume-supported cropping and 7-10 non-legume comparisons. Sites containing crops of each category are given in superscript beside each category number: [1]Jokioinen, MTT (Finland); [2]Viikki, Helsinki (Finland); [3]Lanna, [4]Säby, [5]Stenstugu, SLU (Sweden); [6]Solohead, Teagasc/TCD (Ireland), [7]Trenthorst, vTI (Germany); [8]Osiny, IUNG-Pulawy (Poland); [9]Fundulea (Romania); [10]San Marco Argentano, UDM (Italy); [11]Agrino, AUA (Greece).

Category	Description	Non-legume crops	Legume crops
0[1]	Unsown semi-natural vegetation	*n/a*	*n/a*
1[2,6]	Permanent grassland + legume(s)	*Lolium perenne, Phalaris arundinacea*	*Trifolium repens, Galega orientalis*
2[1,3,4,5,7,8]	Non-permanent grassland (1-2 yrs) + Legume(s)	*Lolium perenne, Dactylis glomerata, Phleum pratense, Festuca pratensis*	*Trifolium repens, Trifolium pratense, Medicago sativa*
3[1,7,10]	Annual non-legume plus legume Intercrop	*Avena sativa, Hordeum vulgare*	*Pisum sativum, Vicia faba*
4[1,8]	Annual non-legume crop undersown with legume(s)	*Hordeum vulgare, Phleum pratense, Festuca pratensis*	*Trifolium pratense*
5[2,9]	Legume forage/green manure		*Medicago sativa, Galega orientalis*
6[7,8,9,10,11]	Annual grain legume		*Pisum sativum, Vicia faba, Vicia sativa, Phaseolus vulgaris, Phaseolus aureus, Lupinus albus, Lens culinaris, Glycine max,*
7[2,6]	Permanent grassland	*Lolium perenne, Phalaris arundinacea*	
8[3,4,5]	Non-permanent grassland (1-2 yrs)	*Phleum pratense, Festuca pratensis*	
9[1,3,4,5,7,8,9,10]	Annual Grain	*Triticum aestivum, Triticum durum, Secale cereale, Triticale (x Triticosecale), Avena sativa, Hordeum vulgare,*	
10[1,9]	Bare/fallow	*n/a*	*n/a*

Main findings from vegetation surveys

A total of 157 non-crop plant species, including a very small number of species complexes where identification at species level was impractical, were recorded across the 11 sites. Of these, six were found to be very common occurring in more than 50% of the surveyed plots, 38 were very rare, recorded from only one sample. Species richness and Shannon Diversity varied significantly between sites (richness

F = 34.57, P < 0.001; diversity F = 5.32, P < 0.001), reflecting both location and crop management. When data were combined into cropping categories (grassland and monocropping ± legumes, or legume intercropping) or into crop category (Table 3, Fig. 8) no clear patterns associated with legume cropping were apparent.

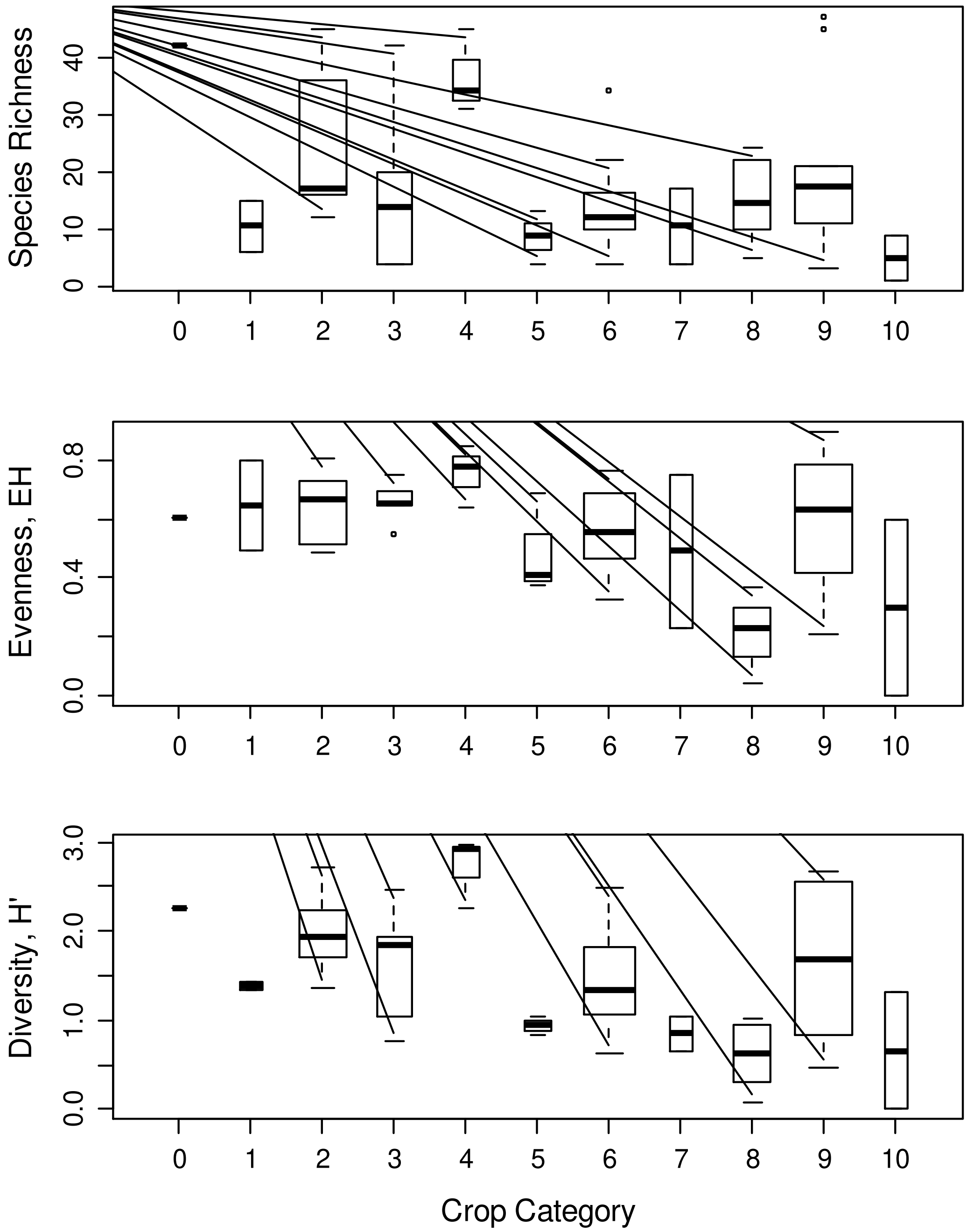

Figure 7. Non-crop vegetation species richness, Shannon evenness and Shannon-Weiner diversity of crop categories. Cropping categories as per Table 3. Data combined from 2011 and 2012 cropping seasons. Width weighted by sample size.

Analysis of community compositions also showed that site played a major influence on the species and their relative abundance within the cropping systems (Figure 9). Samples cluster according to geographic origin, and are influenced by precipitation, temperature and longitude.

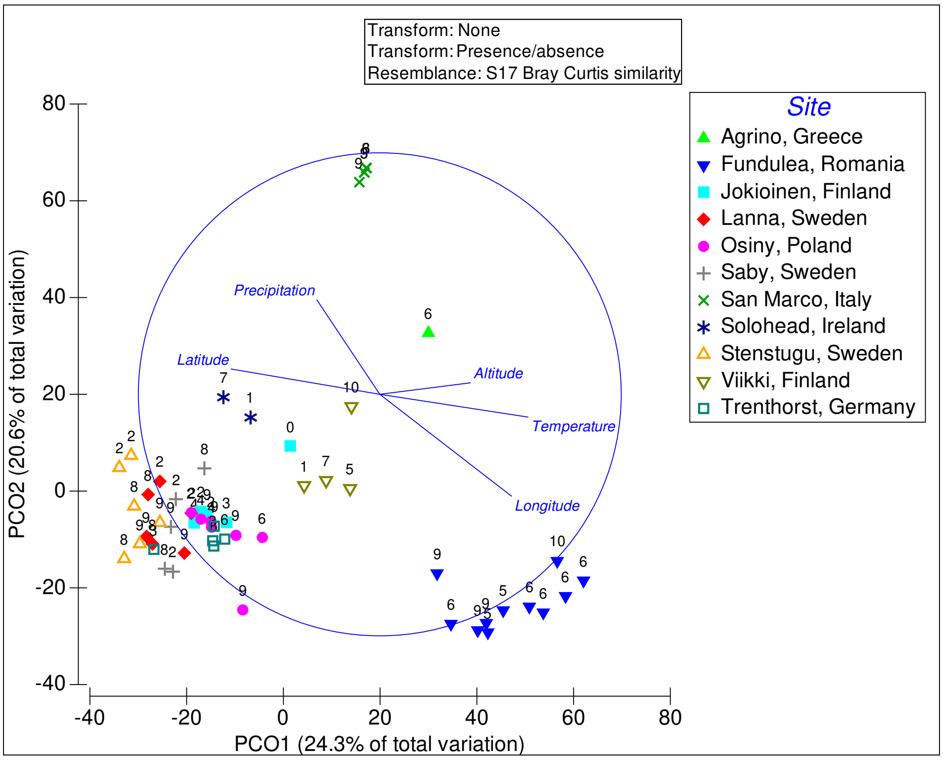

Figure 8. Principal coordinates analysis of non-crop vegetation communities from 2011 and 2012 field surveys showing environmental data vectors. Cropping categories as per Table 1.

Main findings from earthworm surveys

A total of 13 species of earthworm (*Lumbricidae*) were recorded, all of which were present in legume-supported systems. Eleven species were recorded from non-legume crops and seven from unsown plots. Total species richness, abundance and diversity of adults varied significantly between sites, with the highest number of species found at Solohead (Ireland; 11 species - permanent dairy pasture), and the lowest in Osiny (Poland; three species - rotational system). As with vegetation data, when earthworms were combined into cropping categories (grassland and monocropping ± legumes, or legume intercropping) or into crop category (Table 3, Figure 10) no clear patterns associated with legume cropping were apparent.

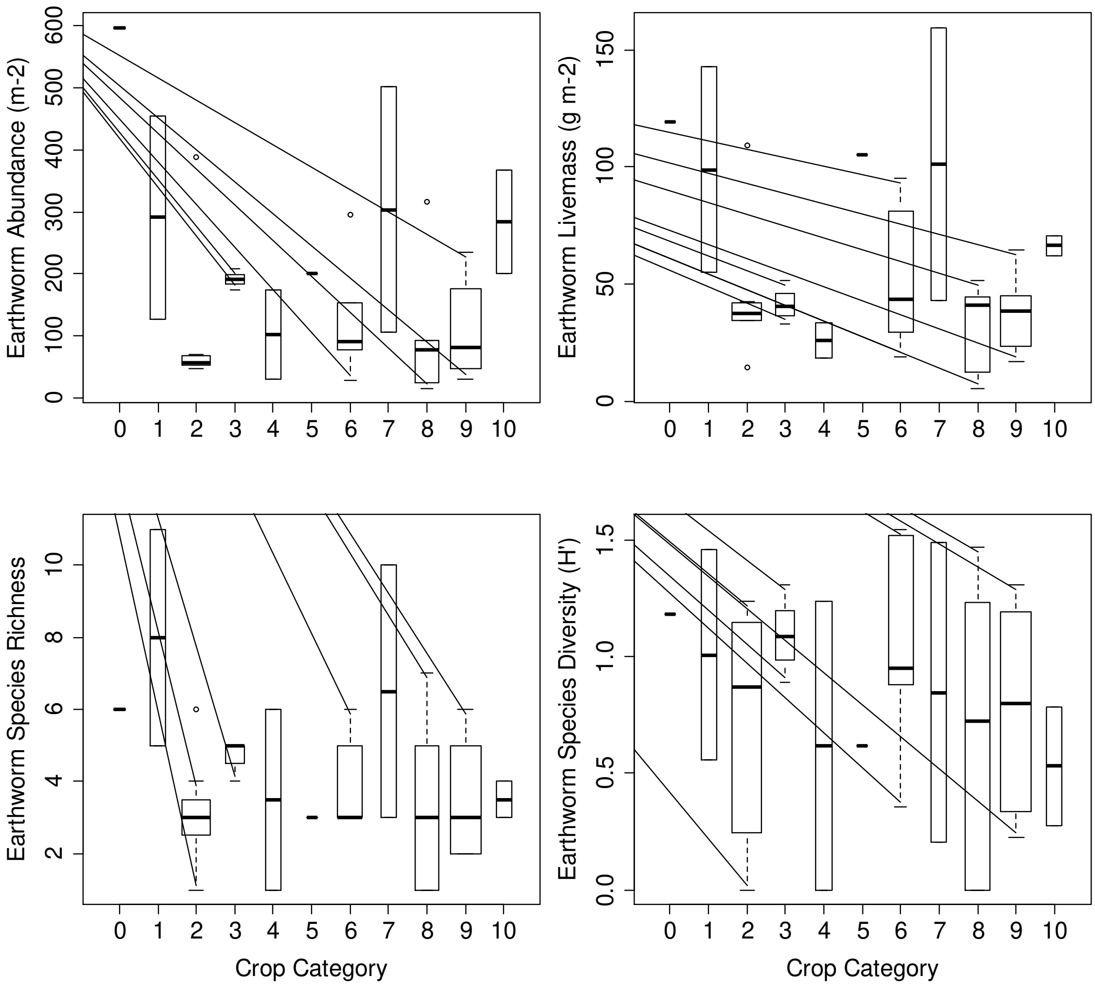

Figure 9. Earthworm abundance, livemass, species richness (adults), and Shannon-Weiner diversity in different cropping categories (as per Table 1). Data combined from 2011 and 2012 cropping seasons. Width weighted by sample size.

Earthworm communities were also clustered by site, with precipitation, temperature, pH, latitude and longitude influencing community composition.

Main findings from invertebrate surveys

Pitfall trapping provides an "activity density" measure rather than absolute abundance and data were standardised to activity density per day. Furthermore, because they record activity, they are not suitable for sampling in small plots, which is why pitfall trapping was confined to three sites with field-level cropping treatments. Samples were identified to Order, where clear differences in community patterns were detected between the three sites. Carabid beetles (*Coleptera; Carabidae*) were identified to species. A total of 71 carabid species were recorded, with communities clearly different between the two continental pedoclimatic sites (Osiny, Poland and Trenthorst, Germany) and the boreal site (Jokioinen, Finland). In addition, semi-natural or unsown fields and short-term grass/legume leys contained distinct carabid assemblages.

Soil faunal activity

Bait-lamina assays were conducted to investigate soil fauna feeding activity at Solohead (Ireland), Jokioinen (Finland) and Trenthorst (Germany). Overall bait consumption (% bait holes perforated) was similar at Solohead and Jokioinen and higher at Trenthorst (vTI). Bait consumption was recorded over a time series to investigate rates of consumption for different crop, but the apparently higher rate of bait consumption in legume monocropping was difficult to interpret given the lack of replication within and between sites. In the mixed rotation at Jokioinen the cereal/legume row intercropping had similar levels of soil fauna feeding activity to semi-natural unsown vegetation; whilst grass/legume leys, cereal under-sown with a grass/legume mixture and cereal mono-cropping, all showed lower feeding activity. At Trenthorst, row intercropping showed higher feeding activity than the presence of a legume crop, with both legume and non-legume (cereal) mono-crops having higher feeding activity than the intercropped system. In permanent dairy pastures at Solohead feeding activity was lower in the conventional *Lolium perenne* treatment than in the legume-supported *Lolium perenne/Trifolium repens* treatment.

Conclusions of biodiversity studies

Differences in non-crop vegetation, earthworm, ground-active invertebrate and *Carabidae* communities, as well as soil fauna feeding activity, detected between crops across Europe. At the site level, a lack of treatment replication and suitable control treatments made the quantification of specific crop effects difficult. We have shown that certain management factors such as crop duration (permanent and semi-permanent grass vs annual crops) have an impact on some aspects of biodiversity (both positive and negative), despite the variation caused by site and climatic factors.

Legume-supported cropping has the potential to be beneficial within sustainable agricultural systems. We do, however, strongly suggest that the practice of stating ‘legume cropping is beneficial for biodiversity’ without specific justification relevant to the system under investigation should be discouraged as it is misleading. If such clear cut impacts were immediately obvious, there would have been evidence for them in this study despite the drawbacks associated with field site design.

NITROUS OXIDE EMISSIONS

Mike Williams, Trinity College Dublin, Ireland

Measurement of the greenhouse gas nitrous oxide was a key part of the environmental impact assessment of legume cropping in Legume Futures. Two important metrics were developed from the measurements; an emission factor for nitrous oxide emissions from legumes, and the assessment of nitrous oxide emission intensity with respect to crop yield for grain legumes.

Emission factor

Nitrous oxide (N_2O) makes up a large proportion of agriculture's contribution to greenhouse gas emissions. In addition to being a powerful greenhouse gas with a global warming potential of 298 times greater than carbon dioxide, N_2O is also involved in the destruction of stratospheric ozone (Reay, 2012; Crutzen, 2001). The close link between N_2O emissions and agricultural production arises as a result of the role of nitrogen in driving emissions. At a global level, there is a clear link between increases in fertiliser nitrogen use and the growth in N_2O emissions which show a long term growth rate of 0.5% (Tilman, 2002). However, agriculture receives nitrogen inputs from a variety of sources. Up until recently it had been assumed by the IPCC that a similar proportion of this N input was released as N_2O regardless of source. However, a number of reviews highlighted that where N was provided by biological nitrogen fixation (BNF) the associated N_2O emissions were significantly lower and in many circumstances no different to unfertilised control environments (Bouwman, 2002; Rochette, 2005). This led to revisions of the national reporting guidelines prepared by the IPCC with the recommendation that no N_2O emissions would be associated with inputs of N by BNF (IPCC, 2006). The evidence for this revision remains somewhat circumstantial, and furthermore the extent to which decomposition of residues from legume plants contributes to emissions is highly uncertain (Baggs, 2000). A major aim of Legume Futures was therefore to relate measured fluxes of N_2O from legume crops to calculated rates of BNF using plant biomass data harvested over the same measurement period.

Emission factors (EF) are estimates of the proportion of an N source emitted as N_2O. They have mostly been applied to studies of fertiliser and manure N, but allow a useful comparison to be made with biologically fixed N. Emission factors developed in this project for biologically fixed N were calculated by first subtracting a background N_2O flux from individual site data of 1 kg N_2O-N ha^{-1} y^{-1}. This was assumed to represent according to present IPCC reporting guidelines, N_2O derived from plant residue and atmospheric deposition (IPCC, 2006). As plots receiving little or no inorganic N (Italy) were used, the remainder of the N_2O flux reflects N inputs into the soil by BNF over the growing period of the crop. Hence emission factors for legume BNF are:

(1) $EF_{BNF} = (N_2O_{growing\ period} - N_2O_{background\ growing\ period})/BNF_{growing\ period} \times 100$

BNF was measured over the N_2O measurement period of the crop by the ^{15}N natural abundance method using a standard measuring protocol based on methodologies listed in Unkovich et al. (2008). Sampling of both legume and adjacent non-legume reference plants were made at the peak period of BNF (early podfill), and at the end of the growth period of the crop. Samples were dried and milled before atom% ^{15}N was determined at the Stable Isotope Facility at JHI, Dundee (full details of the methods used available from Stoddard and Williams 2011). The proportion of N derived from the atmosphere (%Ndfa, in the legume), was calculated by the following equation:

(2) $\%Ndfa = (\delta^{15}N\ \text{non-legume} - \delta^{15}N\ \text{legume}) / (\delta^{15}N\ \text{non-legume} - B)$

where B is the ^{15}N natural abundance of the legume grown either in hydroponics or in sterilized soil with no N source other than atmospheric N_2. To account for N in the root the final BNF values were multiplied by 1.6 (Unkovich et al. 2010).

For sites where the ^{15}N natural abundance method had not been used, a variation of the N-balance method was adopted. Here, total biomass N of the plant was determined using the root:shoot ratio and root N constants and the proportion of total biomass N multiplied by literature %Ndfa values to give BNF over the growing season in kg N ha^{-1}. As BNF data were provided from two different methodologies it was necessary to apply a correction factor to reduce experimental bias as illustrated in Figure 11.

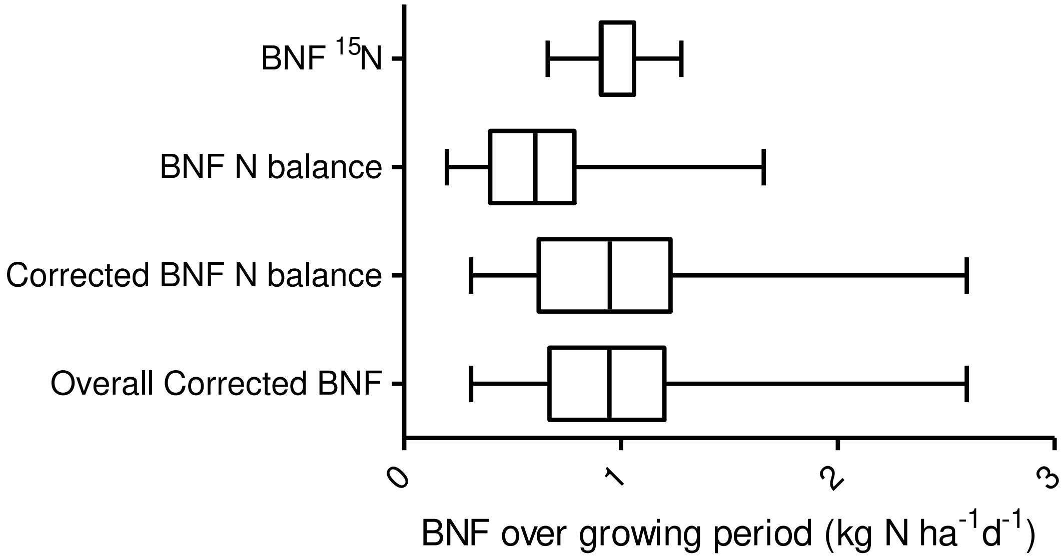

Figure 10. Box and whisker plots for BNF data from ^{15}N natural abundance and N balance methodologies. Each box represents the 1st, 2nd and 3rd quartile with the bars representing the minimum and maximum points in each case.

Figure 12 presents the calculated emission factors (EF) for BNF calculated from data provided from Finland (Galega), Greece (common bean), Italy (faba bean) and Scotland (faba bean, pea and winter bean). Summary statistics for EF (mean, standard error, min, max, first, second and third quartiles) were calculated for the combined data set and for each crop and are given in Table 5. The mean EF for legume BNF for faba bean was estimated at -0.0004 ± 0.04% whilst for pea was estimated at 0.35 ± 0.10%. Other values were 0.7 ± 0.09% for Galega, -0.15 ± 0.01% for common bean and -0.24 ± 0.02% for winter bean.

A significant number of data points are negative such that the median value for the bean EF is below zero and that for the whole data set just above at 0.03%. A wider range of data exists for pea and here the median value is the highest at 0.2%. Of the calculated EF values, 48% lie below zero with a clear skew towards the more widely distributed bean data. For these data sets the IPCC background N_2O emission value was higher than the measured flux and clearly under these assumptions N_2O from BNF is insignificant. Fifty two percent of the EF data though were above zero showing a bias towards the Scottish bean and pea data, and the Finnish Galega data. The majority of these positive values came from the Craibstone (in Scotland) field plots planted with pea, indeed only one EF value for pea was negative in this respect.

Assuming a theoretical value for EF from legume BNF of zero, in accordance with the present IPCC assumption of not including BNF in reporting of N_2O emissions, then a one sample t test showed the mean EF values for common bean, winter bean, pea and Galega to be statistically different from zero.

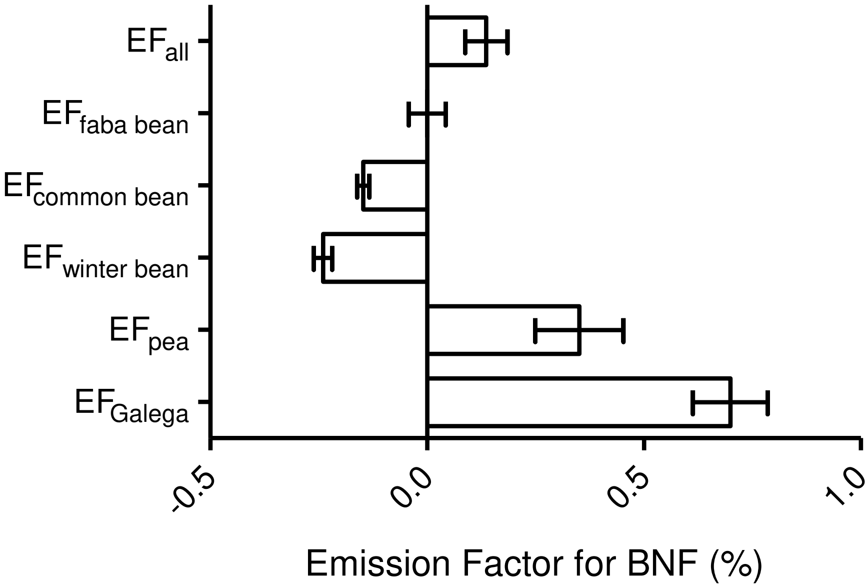

Figure 11. N_2O emission factor for legume BNF (mean +/- standard error)

Table 4: Summary statistics for N_2O Emission Factor for legume BNF.

	EF_{all}	$EF_{faba\ bean}$	$EF_{common\ bean}$	$EF_{winter\ bean}$	EF_{pea}	EF_{galega}
Number of values	79	37	6	4	28	4
Minimum	-0.40	-0.40	-0.20	-0.29	-0.25	0.51
25% percentile	-0.18	-0.25	-0.18	-0.28	-0.04	0.54
Median	0.03	0.01	-0.15	-0.24	0.20	0.68
75% percentile	0.36	0.21	-0.12	-0.20	0.61	0.87
Maximum	2.03	0.49	-0.11	-0.19	2.02	0.92
Mean	0.14	0.0004	-0.15	-0.24	0.35	0.70
Standard Error	0.05	0.04	0.01	0.02	0.10	0.09

The question as to whether such differences in EF values between crops are statistically valid, accepting dominance of the Craibstone data in the overall analysis, may be tested by a two way analysis of faba bean and pea data from cultivar trials at this site. Here two years of data exist for bean and pea incorporating three cultivars of bean and two cultivars of pea grown over the two years, 2008 with an annual rainfall of 899 mm and 2009 with a rainfall of 1160 mm. Figure 13 illustrates the mean EF values from this cultivar trial.

Results from an unweighted means analysis of the combined data showed a significant interaction between cultivar (bean and pea) and year and that cultivar accounted for 35% of the total variation. A Bonferroni post hoc analysis highlighted significant differences between the bean and pea cultivars for 2008 ($P < 0.001$). The lower EF for the pea cultivars in 2009 or the increase in EF for the bean cultivar B in 2009 was not due to any change in BNF but to significant changes in the measured flux of N_2O from the experimental plots.

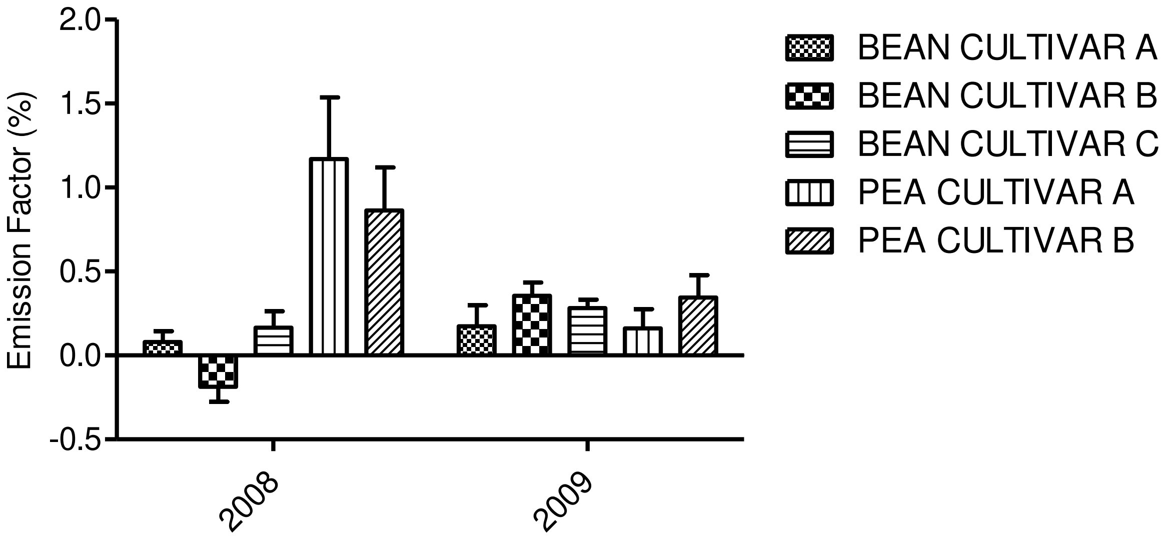

Figure 12. Emission Factors for legume BNF (mean ± standard error) calculated for the bean and pea cultivar trial from Craibstone Estate, Scotland.

Conclusions – Emission Factor

The question remains if BNF should be considered a source of N_2O in calculating N_2O fluxes from legume cropping. As the observed data is not partitioned between BNF and residue decomposition our assumption was that subtracting a background flux of 1 kg N_2O-N ha^{-1} yr^{-1} from the measured emissions of N_2O approaches a theoretical value for BNF derived from N_2O. As such, results considered here suggest N_2O from BNF may be at least dependent on crop and rainfall. Faba and common bean may have a lower emission factor for BNF than for pea and the cultivar trial from the Craibstone Estate supports this view statistically.

Growing plants may influence the N_2O flux to the atmosphere in a variety of ways from providing carbohydrate substrate directly through root exudates and root turnover (Qian et al. 1997; Mounier et al. 2004; Henry et al. 2008; Broeckling et al. 2008; Philippot et al. 2009), through anatomy of the stem and leaf (Baruah et al. 2012) and in the case of legumes, through differences in nodule and rhizobial activity (García-Plazaola et al. 1996; Pappa et al., 2011). It has been reported that N_2O emissions are drastically increased in the late period of a legume crop, suggesting that senescence and decomposition of roots and nodules contribute to emissions (Inaba et al. 2009). Emissions from nodulated soybean were several times higher than from non-nodulated soybeans, especially degraded nodules in the late growth period. N_2O emissions can also be mitigated in soils by inoculation of *nosZ*+ and non-genetically modified organism *nosZ*++ strains of *B. japonicum* at the field scale (Itakura et al. 2013).

Irrespective of management, species and cultivar, differences in N_2O flux may occur which would influence the emission factor observed. Rainfall would determine the anaerobic nature of the soil and hence both the rate of denitrification and diffusive properties of the soil (Davidson, 1991; Davidson et al. 2000; Smith et al. 2003) which itself would be determined by the organic carbon status and percentage clay fraction of the soil (Maag, 1996; Smith, 1998; Beauchamp, 1980).

Whether the estimates for N_2O flux from legume BNF are significant compared with fertilized systems ultimately depends on the annual rates of BNF. An example for faba beans and peas will be used with calculations shown in Table 5.

Table 5. Annual fluxes of N_2O as calculated from estimates of BNF and using derived emission factors for legume BNF

Crop	BNF (kg N ha^{-1} y^{-1})	EF_{crop}	EF_{all}	N_2O (EF_{crop}) (kg N_2O-N ha^{-1} y^{-1})	N_2O ($EF_{general}$) (kg N_2O-N ha^{-1} y^{-1})
Faba bean	299	-0.0004	0.14	-0.001	0.41
Pea	393	0.35	0.14	1.38	0.55

Assuming an overall emission factor for BNF of 0.137% yields an annual flux of N_2O of 0.41 kg N_2O-N ha^{-1} for beans and 0.54 kg N_2O-N ha^{-1} for peas or approximately 40 to 50% of the default background flux of N_2O used by the IPCC to account for mineralisation of crop residues and atmospheric deposition. In the worst case scenario for peas using the crop specific emission factor of 0.351% then the annual flux of N_2O-N to the atmosphere from BNF would be 1.38 kg N_2O-N ha^{-1} or approximately 140% of the default background flux value. These estimated annual fluxes combined with the default IPCC background flux, (1.12 to 2.38 kg N_2O-N ha^{-1} y^{-1}) are well within the range published by Gregorich et al. (2005) and Rochette and Janzen (2005) for leguminous crops of 0.3 to 4.7 kg N_2O-N ha^{-1} y^{-1} but considering the significant proportion of background flux they represent would argue that legume BNF is an important source of N_2O flux in the field and that notice of this should be made in future calculations of N_2O flux from agricultural land. However, practicalities of determining BNF are problematic. Whilst these can be reduced by adopting the simpler N balance method, a more pragmatic approach would be to continue with the present IPCC methodology, the essential comparison being with fertilised cereal and pasture systems where annual N_2O fluxes may range from 0.1 to 19 kg N ha^{-1} y^{-1} (Jensen et al. 2011).

Nitrous oxide emission intensity

Legume supported cropping systems may reduce GHG emissions from agriculture. Studies of GHG mitigation have in the past focused on emission reductions that can be achieved per unit area of land, aligning with policies that set targets for national GHG emission reductions. For this purpose, GHG emission intensities are expressed per unit of product (all emissions divided by all saleable outputs) known as *emission intensities*, hence cropping practices, especially those associated with nutrient inputs, need to be optimised in relation to emission intensities (Thorman et al. 2014). Yields per hectare are also important through their indirect effects on land-use-change, so it is important that studies of nutrient use efficiency and N_2O emissions are expressed against crop yields.

Emission intensities provide an important metric that can be used to lower emissions from the agriculture sector without simply displacing emissions elsewhere (Bonesmo et al. 2012). Few studies have compared losses of N_2O from legume based systems in relation to grain yield production and so the effects of different climatic zones and soil conditions on emissions and emission intensities are poorly understood. Studies that have assessed N_2O emissions from leguminous crops (Rochette and Janzen, 2005) found that legumes can increase N_2O emissions during the cycle, but the source of this increase was uncertain. There is concern that if global food security requires increased production, this should be achieved without expansion of the cropped area, hence mainly though increased yields. Legume Futures in its programme of N_2O measurement from a variety of legume cropping systems across a selection of participants in different countries (Greece, Italy, Romania, Spain and UK), has expressed the N_2O production in terms of emission intensity to highlight the role of climate and crop management in reducing GHG emissions per unit of crop yield.

Figure 14 shows both crop yield and cumulative N_2O emissions for various crop management scenarios in our Italian sites incorporating barley, faba bean and pea. Here the greater the distance between the bar and the marker in each case, the lower the emission intensity for N_2O. Clearly legumes in both rotation and intercrop scenarios were promising in significantly reducing emission intensities compared with cereal monocrops. However, collectively, emission intensity values vary according to climate as illustrated in Figure 15 such that crop choice and country become influential. When expressed on an area basis, emissions from the UK and Romania were generally higher than those in Greece, Spain and Italy. This is likely to have been due to the higher soil moisture during the summer months in these countries. Rainfall during the summer months combined with nitrogen inputs from crop residues manures would be expected to contribute to high fluxes of N_2O (Flechard et al. 2007; Rees et al. 2013). By contrast in the drier Mediterranean soils emissions during the summer months generally tend to be low (Barton et al. 2011; Sanchez-Martin et al. 2010).

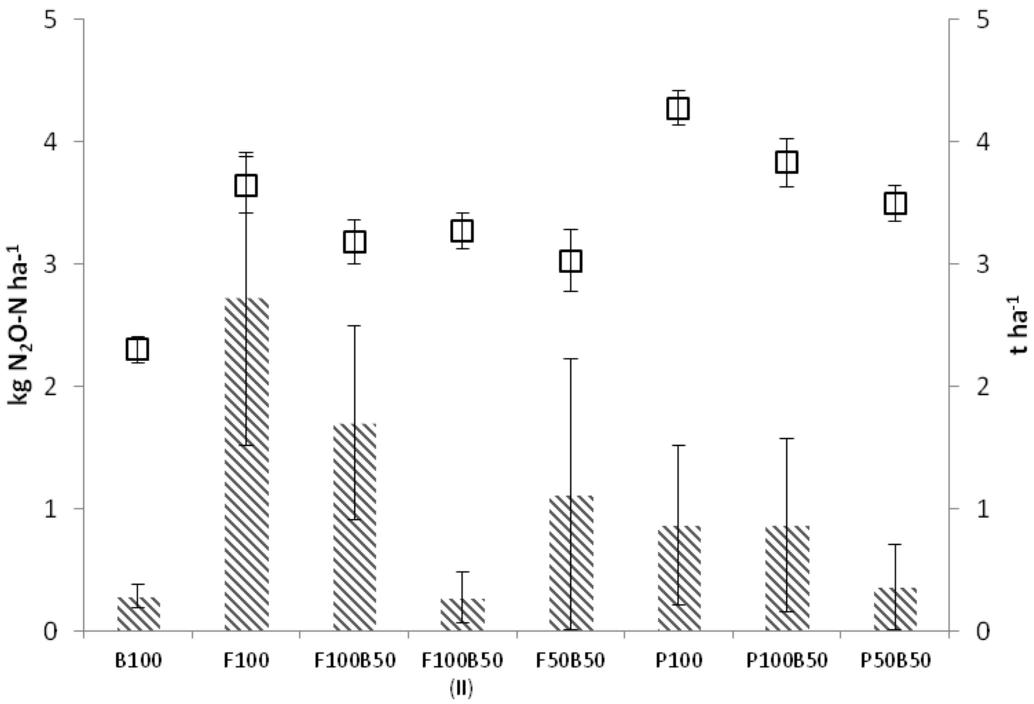

Figure 13. Cumulative N_2O fluxes (g N_2O-N ha^{-1}) from sowing to harvest presented in bars, and grain yields (t ha^{-1}) presented in markers for crops grown at the Italian sites. B100, F100 and P100 refer to barley, faba bean and pea monocrops whilst FB and PB refer to faba bean/barley and pea/barley intercrops respectively. The numbers refer to relative seed density in each treatment. The greater the distance between the bar and marker in each case, the lower the emission intensity.

Emission intensities did not follow the patterns of area-based emissions (Figure 15). The quantity of biomass produced is an important determinant of emission intensity. Therefore high crop yields observed in Italy and Greece combined with lower emissions resulted in lower emission intensities in these areas. A reverse pattern was observed in the UK where higher emissions coupled with lower crop yields contributed to high emission intensities.

Conclusions – Emission intensities

Including legumes in farming systems can significantly reduce GHG emissions and emission intensities. This benefit is apparent across continental Europe, although the magnitude and the nature of appropriate legume crops may vary from country to country. N_2O emission intensities can be significantly higher in winter crops compared with spring-sown legumes and cereal monocrops growing at the same experimental site.

The magnitude of these effects is highly sensitive to management. Those management practices which enhance biomass production are likely to be most successful in reducing emissions intensities (Cui et al. 2013). In addition, legumes have an effect on the following crop related mainly to cumulative fluxes than crop yields (Pappa et al. 2012; Pappa et al. 2011). Seeding patterns have an important role in the flux production, such as replacement or additive designs, and soil management practices, such as no tillage and tillage.

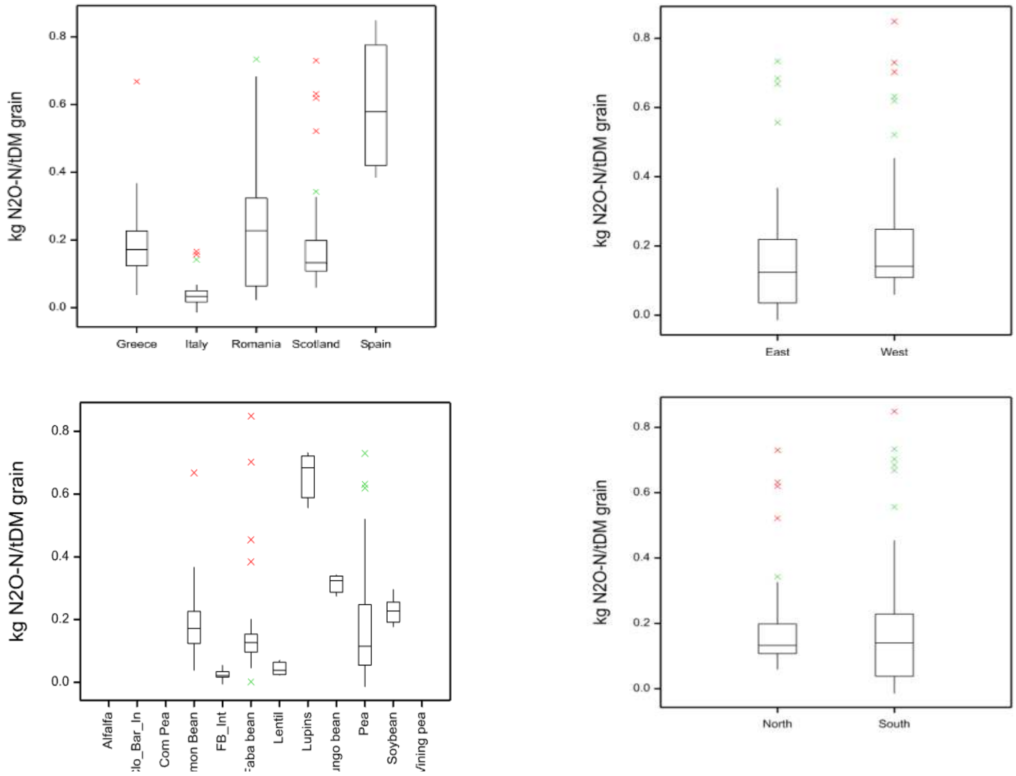

Figure 14. Emission intensities per country, latitude, longitude and crop species based on plot data.

NITROGEN FIXATION BY LEGUMES IN EUROPEAN AGRICULTURE

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Biological nitrogen fixation (BNF) is a characteristic of legumes. Large, continental- or global-scale estimates of BNF have been attempted with varying degrees of refinement (e.g. Yang et al. 2010 for Canada) but all cite the lack of crop-specific N fixation data as one of the major uncertainties. Previous attempts to estimate BNF have tended to calculate the amount of N fixed as the product of the land area cultivated and fixation per area. However, as yields range more than 10-fold across species, countries and years, it is not desirable simply to use legume areas for each country and convert these to overall fixed N using an average figure for BNF. Hence we aimed to produce an improved estimate for BNF across Europe using the most detailed available data and robust scientific logic.

Two different methodologies were used within Legume Futures for estimating BNF, one for forages and one for grains, as necessitated by the available data (Baddeley et al. 2014). The amount of N fixed by forage legumes and legume-grass systems was predicted by a combination of data from the Common Agricultural Policy Regionalised Impact (CAPRI) model, area data from Eurostat, and improved, country-specific N fixation coefficients. The latter were determined by the N fixed per hectare and the proportion of the grassland that is assumed to include a legume component. For grain legumes, we constructed a detailed N partitioning model that calculated N fixed, N balance (N fixed – N in grain) and N residue (N in total plant – N in grain) for each crop, relative to grain production (Table 6). These figures were combined with production data extracted from the FAOstat database to give quantities of BNF in EU27. Moisture content was set at 14% as that is the normal reporting value in Europe, and the N to protein conversion factor to 6.25 as is widely used. Other coefficients were derived from a range of literature (see Supplementary Table, Appendix 1). All data were from 2009, the latest complete dataset in CAPRI at the time.

The calculations of N capture and harvest (Table 6) show that although chickpea fixes relatively little N, it leaves the most behind per tonne of grain, because of its low Ndfa value. Vetches, lupins and faba bean all fix over 60 kg of N per tonne of grain, and vetches and faba bean leave over 20 kg of this behind. The area-weighted mean N fixation for all forage legume systems was 7.7 kg ha^{-1}, some 50% higher than the estimates used in many models.

Converting these data to a total, based on grain legume yields and forage areas, indicated that 811 Gg of N was fixed in the EU27 by agricultural legumes in 2009, slightly less than the mean estimate of 1.12 Tg based on four European N budget models (De Vries et al. 2011). Most of the difference occurred because the N budget models allowed for ~5 kg ha^{-1} of N fixation by free-living microbes in all non-legume arable land, in contrast to our focus on legumes.

The total amount of N fixed by forage legumes was 586 Gg, comprising 414 Gg from permanent pastures and 172 Gg from temporary pastures. For grain legumes, the total fixation of 225 Gg was dominated by pea, faba bean and soya bean, which were responsible for about three quarters of N fixed (Fig. 16). A large proportion of the total N was fixed by a fourth category of crop, “pulses”, but this is an amalgamation of many minor grain legume species together with varied reporting of some of the major species. In particular, comparison of Eurostat and FAOstat data show that UK faba bean is treated as a "pulse" in FAOstat.

Both approaches predicted detailed crop- and country-specific figures for BNF fixation by legumes that are broadly comparable with previous estimates but which, for the first time, take into account the large differences in yields across Europe.

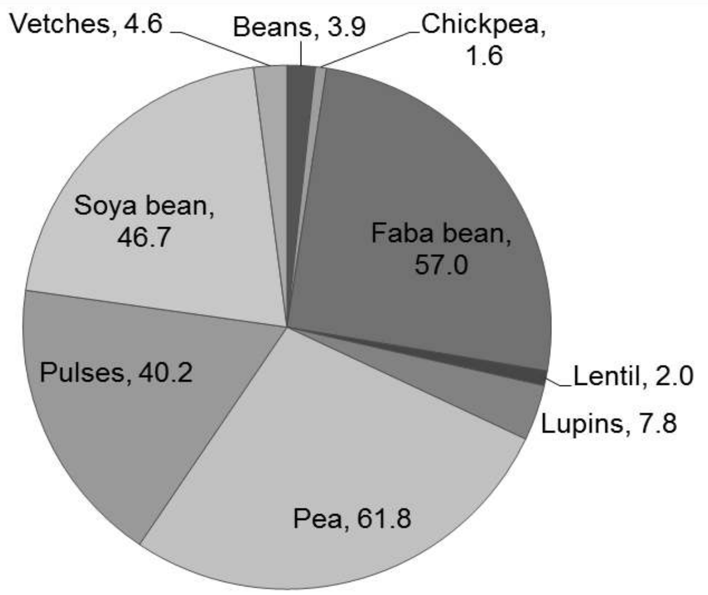

Figure 15. Calculated quantities of total N fixed in the EU27 by grain legume crops in 2009 (Gg) as reported by Baddeley et al, 2014.

While the amount of atmospheric N fixed into farming systems is likely to increase with increasing cultivation of many species of grain legumes, this is unlikely for common bean and soya bean, both of which apparently reduce soil N reserves (Table 6).

Estimation of BNF by forage legumes would be greatly facilitated by improved estimation of the proportion of grasslands that include legumes and information on the relative inclusion rates.

Table 6. Constants (bold) and calculated values used to derive estimates of fixed N and N balance for FAO classes of grain legumes. All calculated quantities are relative to one tonne (1 Mg) of grain production. Sources of coefficients are given in Appendix Table 1.

	Common bean	Faba bean	Chick-pea	Lentil	Lupins	Pea	Soya bean	Vetches
Grain protein concentration (g g^{-1})	0.25	0.29	0.22	0.29	0.36	0.25	0.40	0.29
Grain N concentration (g kg^{-1})	33.8	40.2	30.0	39.6	49.1	34.4	54.8	39.9
Harvest index	0.48	0.49	0.31	0.42	0.44	0.51	0.52	0.34
N harvest index	0.83	0.68	0.80	0.65	0.84	0.73	0.73	0.79
Above ground biomass (t)	1.79	1.76	2.77	2.07	1.96	1.70	1.66	2.53
Above-ground N concentration (g kg^{-1})	40.8	59.5	37.3	61.0	58.5	47.2	75.0	50.5
Root:shoot ratio	0.26	0.23	0.44	0.37	0.28	0.11	0.20	0.35
Root biomass production (t)	0.475	0.404	1.221	0.767	0.551	0.187	0.331	0.885
Root N concentration (g g^{-1})	0.022	0.022	0.014	0.014	0.012	0.022	0.017	0.029
Root N production (kg)	10.3	8.9	17.1	10.7	6.5	4.1	5.7	25.8
Proportional rhizodeposition	0.15	0.18	0.53	0.15	0.17	0.12	0.20	0.15
Rhizodeposition (kg)	7.7	12.6	28.8	10.8	11.1	6.2	15.7	11.4
Total N production (kg)	58.7	81.1	83.2	82.5	76.1	57.4	96.5	87.7
Proportion of N derived from atmosphere, Ndfa	0.44	0.77	0.50	0.70	0.82	0.70	0.52	0.72
N fixed (kg)	26.0	62.4	41.6	57.7	62.4	40.2	50.2	63.2
N balance (kg)	-7.9	22.2	11.6	18.1	13.3	5.8	-4.6	23.2
Residual N (kg)	24.9	40.9	53.2	42.8	27.0	23.0	41.7	47.8

LAND USE AND SOIL CARBON EFFECTS

Kairsty Topp, SRUC, UK

In the past 50 years, production of legumes in Europe has declined, despite an increase in the consumption of legumes (particularly soya). International trade now allows the movement of animal feeds from distant parts of the world, creating local and global imbalances in nutrient cycling processes. An analysis of international trade in agricultural products reported that in 2004 the nitrogen content of imported grain (mostly soya) to Europe from S America was 2,318 Tg compared to 1,766 Tg of internally traded grain N (Galloway et al. 2008). Such imbalances have encouraged policy makers within Europe to explore opportunities to increase European legume production; a topic which is central to the Legume Futures project. Despite considerable environmental benefits of growing legumes, such as enhancing soil properties as well as reducing N surpluses, the production of legumes is declining in Europe, while their consumption is increasing. The decrease of production is due to the lower and more uncertain revenue they bring to farmers, while the increase in consumption is due to increased demand for animal products, which requires imported soya.

An analysis undertaken within Legume Futures compared the GHG emissions legumes grown in Europe with those grown elsewhere. The overall impact of producing more grain legumes in Europe gives a small climate benefit compared to importing soybeans to Europe. Approximately 280 kg CO_{2eq} are avoided for each hectare producing pea instead of wheat in Europe. Similarly, 175 CO_{2eq} are avoided for each hectare faba bean produced instead of wheat in Europe. This analysis which included a consideration of Land Use Change effects, provides justification for increasing European Legume production.

The CAPRI model was used to evaluate a range of policy interventions that could be used to increase the cultivation and production of European legumes. CAPRI (Common agricultural policy regional impact model) is a linked economic-biophysical model that has been extensively used to investigate the impact of policy interventions in European agriculture. In this study, four scenarios were compared: (1) A premium scenario to promote legume cultivations whereby farmers would be paid for the area of cultivation, (2) Ecological Focus Areas which will be used within the CAP as justification for direct subsidy payments, (3) A meat tax levied on meat consumption and an equivalent subsidy is introduced for human consumption of vegetable protein, (4) the reference scenario which assumes business as usual. The results showed that the biggest increases in areas of grain legume were achieved by coupled support policies. In the case of grasslands, there were relatively small projected changes (<5 %) in the utilisable agricultural area associated with the policy interventions studied. However grasslands are important sources of agricultural GHG emissions and increasing the proportion of legumes that they contain could be an effective mitigation strategy.

One consequence of increasing cultivation of European legumes would be decreased imports of legumes from regions outside the EU. This could have beneficial impact on land use for two reasons. Firstly it could reduce landuse change pressures in soy exporting countries and therefore reduce the land use derived GHG emissions. Secondly it would increase the cultivation of European grain legumes. Our research shows that each hectare of European wheat that is replaced by peas saves approximately 280 kg CO_{2eq} y^{-1} in net GHG emissions.

Carbon cycling

Legumes can also have benefits to carbon cycling through the effect they have on the soil. The incorporation of legumes into the farming system tends to improve the soil structure due their rooting characteristics. They also tend to increase the soil organic matter which can result in lower soil erosion and increased water retention, which may be a benefit under future climates where droughts are projected to be more prevalent. The increase in water holding capacity and soil organic matter can have positive benefits on the yield of the proceeding crop.

The benefit of legumes in terms of soil carbon is more clearly seen with forage legumes than for grain legumes (Jensen et al. 2012). Ruz-Jerez et al. (1994) and Mortensen et al. (2004) have reported higher soil organic carbon contents under grass-legume mixtures than in pure grass swards. However, Schils et al. (2005) noted that grass-clover mixtures required to more frequent reseeding and hence ploughing than grass swards which will tend to reduce soil carbon. The evidence from the trials would support the fact that forage legumes can improve the soil carbon status whereas grain legumes in rotation and intercropped legumes have limited effect, although there is a benefit to soil quality. Notwithstanding, there is some evidence to suggest that the incorporation of legumes on a regular basis into a long-term rotation does lead to increased soil carbon (Jensen et al, 2012). Incorporating legumes which are used as green manures / mulches can lead to an increase in the soil carbon. Nevertheless, regardless of the legume system, the net carbon gain will be affected by the previous cropping history, and this largest effect is observed when short-term leys or arable systems are converted to long-term pastures which include legumes.

Although existing Life Cycle Assessments show the potential for legumes to mitigate the effect of climate change, they tend to underestimate the full potential. This is because the impact of C sequestration is not typically included in the LCAs. However, the reductions in emissions may be offset by the need for more frequent reseeding of pastures (Schils et al., 2005).

SOCIOECONOMIC IMPACTS AT THE FARM AND REGIONAL SCALE

Peter Zander, ZALF, Germany

Economic value of legumes

Grain legumes increase the yield of subsequent crops in the rotation. This precrop effect has been reviewed in detail (Jensen 1997, Luetke-Entrup et al. 2003, Kirkegaard et al. 2008, Peoples et al. 2009a). It is caused by the crops' biology as well as the production techniques typically applied for a crop (e.g. autumn- or spring-sowing) (Kahnt 1986). The precrop effect can be subdivided into 'break crop effect' and the 'nitrogen effect', which typically act in a combined manner (Chalk 1998).

The 'break crop effect' is not specific to legumes but occurs when monotonous rotations, such as those of winter cereals in much of Europe, are 'broken' by a broad-leaved crop or summer cereal such as oats (Robson et al. 2002). Break crops reduce the potential for pests, diseases and weeds and positively affect soil fertility and availability of soil nutrients and water. Reduced leaf diseases accounted for 91% of the yield benefit of legumes in one experiment (Stevenson and van Kessel 1997) and reduction of take-all disease was seen as the most important yield benefitting factor in another (Dyke and Slope 1978). Due to these mechanisms, cereal crops following 'break' crops are reported to yield 15 to 25% more than cereals grown continuously (Kirkegaard et al. 2008).

In some regions legumes tend to be more risky crops in arable farms than cereals as is the case in Brandenburg and Sweden. In Brandenburg especially, high yield fluctuations can cause negative gross margins. The yield volatility is mainly due to the lack of genetic progress in leguminous plants. In Germany for instance, only one breeding company has a full breeding program for faba beans and peas. For winter wheat, however, there are 16 full breeding programs. The yield of cereals has probably therefore increased faster in recent decades as a result of this investment.

In order to obtain information on cropping data, agronomy and economics of legumes and all alternative crops, a large survey was conducted in five case regions across the Legume Futures network. The core economic data collected throughout the survey are stored in a database that is publicly accessible (www.legumefutures.eu). The economic analysis within our case study regions showed that the inclusion of pre-crop effects and consideration of N-savings changes the economic valuation of legumes at farm level and leads in some regions to different management decisions (Reckling et al. 2014a). The economic performance of individual legume crops is unprofitable or at least unfavorable compared to other crops in most regions, largely due to their low yields and resulting low gross margins (Table 7), which is in some cases more than 50% lower than in cereals.

Table 7. The economic performance of legume and non legume based rotations in different European regions.

Region	Crop rotation		Annual GM incl. Precrop effect (€ ha^{-1})			
	without legume	with legume	without legume	with legume	Advantage legume rotation	Thereof precrop value
Romania, Sud Muntania	B-RS-W-M-SF	B-RS-W-**P**-SF	334	275	-59	-12
	W-SF-M	W-SF-M-**P**	319	314	-4	-4
		W-SF-M-**SB**		403	84	99
	B-SF-M	B-SF-M-**SB**	130	271	142	189
		B-SF-M-**P**		183	53	86
	W-RS-M-SF-M	W-**P**-M-RS-M	309	482	173	177
		W-RS-M-**P**-M		420	111	114
Sweden, Western Sweden	R-O-R-RS-R-O	R-**P**-R-RS-R-O	486	482	-4	31
	O-W-RS-W-W	O-**FB**-W-RS-W-W	568	525	-43	25
	W-O-W	W-O-W-**FB**	459	422	-37	47
		W-O-W-W-O-W-**P**		444	-15	27
Italy, Calabria	O-B	O-B-**FB**	383	211	-172	9
		O-B-**P**		206	-177	9
Germany, Brandenburg (2)	RS-W-B	RS-W-**P**-W-B	161	120	-41	11
		RS-W-**FB**-W-B		97	-65	11
		RS-W-B-**P**-W-B		101	-60	0
Brandenburg (3)	RS-T-R-R	RS-T-**P**-R-R	91	54	-37	20
Brandenburg (1)	RS-W-W-R	RS-W-**FB**-R	308	198	-110	55
UK, Eastern Schotland	B-RS-W-W	B-RS-W-**FB**-W	799	757	-42	14
		B-RS-W-**P**-W		779	-20	14
	W-O-B-RS-Pot-sB	W-O-B-**P**-Pot-sB	1366	1318	-48	0
		W-O-B-**FB**-Pot-sB		1299	-66	0
AVERAGE			**439**	**425**	**-20**	**42**
Range			91 – 1366	**54 – 1318**	**-177 – 173**	-12 – 189
Comparison						
Hayer et al. 2012 [1]					-20 – 33	
LMC International 2009 [2]					-54 – 0	
Luetke-Entrup et al. 2006 [3]					-31 - +115	

Weitbrecht & Pahl 2000 [4]	70-86	
von Richthofen et al. 2006 [5]	-181 - +7	-4 – 57

Crops: W – wheat, B – barley, O – oat, M – maize, RS – rapeseed, SF – sunflower, Pot – potato; P – pea, FB– faba bean, SB – soya bean

Sources: data in upper part are based on own calculations, data provided by project partners

Comparison is based on:

1 Hayer et al. 2012 (France)

2 LMC International 2009 (Germany, UK, France, Spain, Considered precrop effects: Yield effect on 1st subsequent crop, N fertiliser saving)

3 Luetke-Entrup et al. 2006 (Germany, ploughed and conservation tillage systems)

4 Weitbrecht and Pahl 2000 (Germany, organic production system, high soya value partly for food use)

5 von Richthofen et al. 2006b (Switzerland, Germany, Denmark, France, Spain Considered precrop effects: yield effect on 1st subsequent crop, fertiliser saving, pesticide saving, reduced tillage).

Impact of legumes on farm economy

Crop choice is a sequential management decision that has to fit in with strategic decisions on a farm (Bouma et al. 1999 in Janssen and van Ittersum 2007). With respect to the long-term farming strategy, grain legumes are especially suitable for use in organic farming (due to supply of scarce and expensive organic nitrogen and high-protein feed), for mixed farms (due to higher on-farm feed value than market price), or in zero tillage systems (due to suitability for reduced tillage after the legume crop), than in conventional, purely arable and conventional tillage farms (Recking et al. 2014b).

In specialized arable farms the potential of grain legumes differs between the regions. In regions such as Scotland and Romania the potential of grain legumes is highest (Schläfke et al. 2014). Legumes have competitive gross margins only in these regions. Here they would even be profitable without taking into account the positive pre-crop effects. In Scotland especially, peas and faba beans, depending on the site class and in Romania especially soy beans have a high potential. However, actual land use patterns don´t reflect this potential, which indicates marketing or other barriers to uptake.

On arable farms in Brandenburg, it was mainly peas that had the highest potential. However, their positive effects in crop rotations did not fully compensate the highly negative gross margin, related to low yields. Taking area payments into account brings them into the crop production plans on soil type LBG3 because their gross margin was slightly higher than the area payment minus costs of mulching, which is compulsory in set aside.

In regions such as Calabria or Sweden, despite positive effects of legumes and area payments, these are not sufficient to grow grain legumes on arable farms, as they are the most unprofitable crops because of their low yields compared to non-legumes. Only by cultivating grain legumes on Ecological Focus Areas (EFA) or by paying extra subsidies are they of interest. The most profitable legume in both regions is faba bean.

The cropping pattern of mixed farms was calculated with the help of the linear programming farm model for a mixed farm in Brandenburg and one in Sweden. (Schläfke et al. 2014).

In Brandenburg, with area payments and with area payments according to the new CAP all sites would be cultivated in this mixed farm. The feeding regime calculated in both scenarios with area payments shows that lupines are rather used for feed concentrates than sold at market prices. The share of grain legumes is under area payments with 13% relatively high which shows that grain legumes are undervalued on the market (Table 8). Contrary to the arable farm, the mixed farm uses most of its area – even areas that are under arable conditions not profitable, but which can offer valuable forage.

Table 8. Farm results for a dairy farm in Brandenburg under different situations

	Total land	Set-aside	LBG 1	LBG 2	LBG 3	LBG 4	LBG 5	Dairy cows	Total gross margin	Total premium payments	Area grain leg.	Share grain leg.	Area forage leg.	Share forage leg.
	[ha]	[ha]	[ha]	[ha]	[ha]	[ha]	[ha]	[head]	[€/a]	[€/a]	[ha]	[%]	[ha]	[%]
No area payments	238	19	19	57	94	69	0	76	34204	0	32	13%	13	5%
Area payments 300 €/ha/a	257	0	19	57	94	70	18	82	110431	77100	33	13%	14	5%
Area payments 260 €/ha/a	257	0	19	57	94	70	18	82	100151	66820	33	13%	14	5%

In Västra Götaland the cropping pattern does not change with the introduction of an area payment of about 230 €/ha. The only difference was the higher total gross margin of the farm when receiving an area payment (Table 9). In all rotations grain legumes especially faba beans are included which is totally different to arable farms were a regulation is needed to get grain legumes in the rotations. This means it is more profitable for a farmer to grow grain legumes for animal feed instead of growing them as a cash crop. In total the share of grain legumes is about 14% of the arable land which is already more than required as ecological focus area in the new CAP.

Also forage legumes especially clover grass are cultivated with a share of 45% of the arable area which means it is here the most cultivated crop. Clover grass and faba beans are only used for forage. Spring oat and winter oil seed rape are both used as forage and for sale. Winter wheat and spring barley are only cultivated as cash crops.

Table 9. Farm results for a dairy farm in Västra Götaland under different situations

	Arable land	Set-aside	Dairy cows	Total gross margin	Total premium payments	Area with grain legumes	Share of grain legumes	Area with forage legumes	Share of forage legumes
	[ha]	**[ha]**	**[head]**	**[€/a]**	**[€/a]**	**[ha]**	**[%]**	**[ha]**	**[%]**
No area payments	130	0	81	162311	0	18	14%	58	45%
Area payments 230 €/ha/a	130	0	81	192211	29900	18	14%	58	45%

In Brandenburg and Sweden both grain legumes and forage legumes have more potential for on-farm feeding in dairying. Next to clover grass, lupins in Brandenburg and faba beans in Sweden have the highest potential. Here it seems that farmers are not very familiar with the cultivation of legumes, which indicates the advisory system may have a role to play. However, the inclusion of some legumes in feed is limited by anti-nutritional factors. The relatively high starch content can also promote acidosis in excessive use and in conjunction with high shares of cereals. They should therefore be given in squashed form and thermally treated, as this has a positive effect on their intake and degradability in the rumen. The costs for the treatment is about 65€/t, which depends also on the scale of these processing facilities. Finally, it is recommended not to add more than 4 kg per animal per day in the feed ration (Schläfke et al. 2014).

Farming policy implications, trade and welfare

Turning to policy scenarios, we have three instruments for promoting grain legumes on arable land, one for forage legumes either on arable land or intersown with grass, and one that can affect both grain and forage legumes. Starting with the policies for grain legumes, the hectare premium (such as existed until recently in the CAP for peas, field beans and sweet lupins) appears to be the most effective in increasing the area under grain legumes – although even so it cannot reverse the decline that has taken place in recent years. It leads to a small increase in farmers' incomes (although achieved by arable farmers at the expense of livestock farms). There are positive environmental effects compared to Business as Usual (the reference scenario), but because the effect on land use is small the same is true for any impact of land use change.

This is especially true for the other two grain-legume policies: allowing legumes to qualify for Ecological Focus Areas and providing incentives for consuming more pulses and less meat. However, the EFA policy produces significant results in some countries, which could be a reason for letting member states decide on how to implement EFAs. The subsidy for grain legumes for food produces environmental benefits beyond the mere effect on legume cultivation, because of the concomitant reduction in meat consumption. However, this limited advantage may be undone by more intensive and large-scale farming – pushed by the squeeze on margins in animal production. Average farm incomes decline under this scenario.

The other policy scenario potentially affecting all legumes involves a carbon tax: putting a tax on greenhouse gas emissions from agriculture. In order to make this tax, on balance, neutral to farming as a whole, its proceeds can be returned to the farming sector in the form of a subsidy on farm labour. Such a policy not only makes nitrogen fertilizer more costly (and therefore biological nitrogen fixation an attractive option), but it also puts a price on N_2O emissions and rewards carbon storage in the soil. Depending on the price of emission rights, such a policy can have a significant effect on the area under legumes: an increase of 19% compared to Business as Usual even at the relatively modest price of € 18 per tonne of CO_2 equivalent. There is a slight decline in the livestock sector: 0.5% for dairy, 0.9% for beef, and 0.2% for pig fattening, assuming that the proceeds of the tax are returned to the farming sector. In the poultry sector the effect is positive.

Legumes deliver significant benefits and therefore deserve attention from policy-makers. Neither the costs nor the benefits quoted here are cast in stone – particularly as not all benefits can be easily quantified. Furthermore societal benefits such as reduced nitrate leaching and greenhouse gas mitigation would not appear on the balance sheets of individual farming enterprises. Concerning the cost, i.e. the often lower margins from growing legumes, these can be lessened by conscious policy efforts: research on increasing legume yields, and spreading knowledge on legume cultivation will help to improve the economic performance of legume crops. There are also trends that may lead to a reversal of the decline in legumes: increasing popularity of organic farming, higher prices of fertilisers and of imported soya will all contribute.

Yet, direct incentives such as those modelled by Helming et al. (2014) will also be needed if the trend of decline is to be reversed. Autonomous developments such as cited above will make legumes more attractive, but probably not attractive enough. Whether the social benefits gained by such incentives depends on the value orientation of the policy-maker: whether he or she takes a long-term or a short-term view, and whether the unquantified benefits (increased biodiversity and more sustainable soil management, to name the most important ones) are sufficiently valuable to justify the social cost.

Policy implications at EU level

The policy scenarios we examined using the CAPRI model (Britz, 2008, Legume Futures Report 4.5). The expectation for the reference scenario (business as usual) is that the total area under grain legumes will continue the trend of decline which has been established over several decades. This decline will be smaller than the expected decline in arable land, so the proportion of legumes in arable land will actually increase slightly.

We have shown that most policy scenarios, except for the carbon tax, have only a small effect on the area of grain legumes in the medium term. The carbon tax scenario can have a larger effect, as shown in Figure 17, using the variant where the emission price is € 18 per tonne of CO_{2e} and where the proceeds of the tax are returned to the farmers. That scenario can even reverse the decreases in recent years. The same is true for the autonomous scenario of disruptions in the soya market due to restrictions on GM varieties of soya. For forage legumes, the figures are insufficiently complete. However, their cultivation on arable land increased by 33% in the period 2000-2010 in those 16 EU countries for which figures in both years are available; changes in the percentage of clover in grassland (with which our scenario is concerned) are not known.

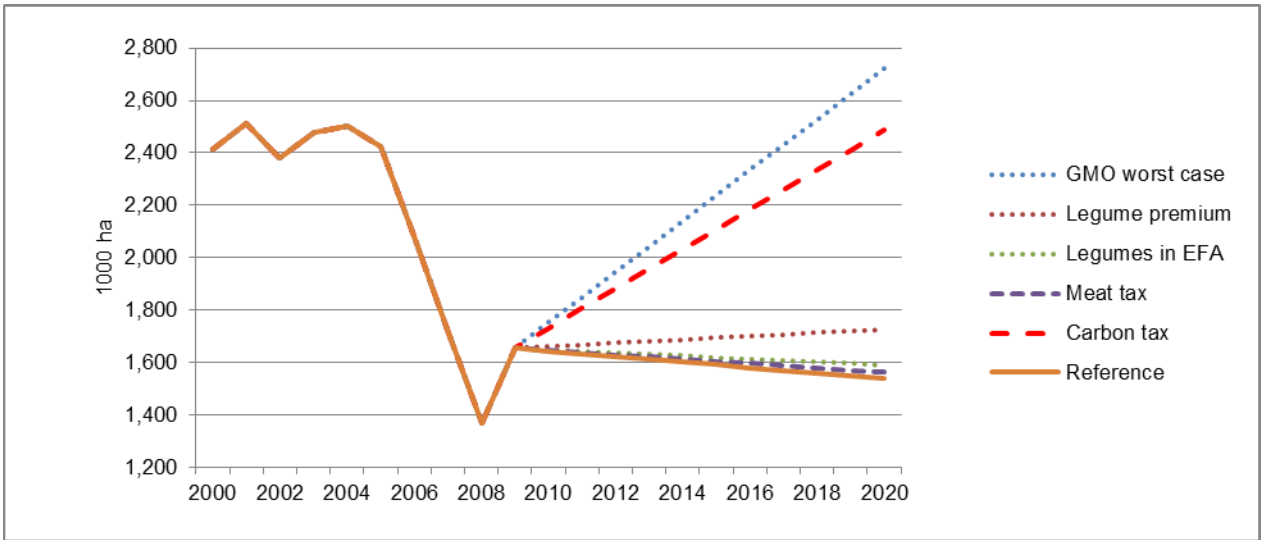

Figure 17. Area cultivated with grain legumes under different scenarios.

The history of legume cultivation over the last 50 years (Figures 7 and 17) shows that arable farmers strongly respond to incentives and disincentives regarding legumes. However, the instruments currently available in the CAP offer only limited scope for steering arable farming in a desired direction.

There are other possible autonomous developments which may influence the area under legumes, which we have not been able to model in the present exercise. One of these is the global food situation. With increasing prosperity and (albeit more slowly) growing population, the global demand for animal products has increased rapidly in recent decades and may be expected to rise further. This will lead to rising demand for soy, and therefore rising prices. Europe may then be forced to grow a larger share of the legumes it consumes within Europe itself. This effect may be reinforced by climate change: although agricultural productivity in parts of southern Europe may decline, in the north it is likely to increase. At the same time, in some parts of the world where the demand for livestock products will rise the most (particularly in Asia), climate change is expected to have a negative impact on agricultural potential (Field, 2014). What happens to legumes in such a situation may be comparable to the GMO scenario modelled here.

Another possibility is a continued rise in the price of fertiliser, especially nitrogen-based compounds. The nitrogen component of inorganic fertilisers is most often in the form of ammonium nitrate or urea, both of which use ammonia as a feedstock. This ammonia is commonly produced from natural gas and the nitrogen in the air, with gas making up the bulk of the production cost. Alternative methods are also highly energy-intensive. Hence, the price of nitrogen fertiliser strongly depends on energy prices. The cost of nitrogen fertilisers rose by over 220% in the period 2000-2011 (see Bues et al. 2013), which means an increase in real terms of 170%. Relative to agricultural producer prices the increase is less spectacular, but still substantial: 63% for wheat and 78% for milk (see Bues et al. 2013).

Consumption of both natural gas and energy in general will undoubtedly increase significantly in the decades to come: the EIA expects an increase in the consumption of natural gas of 56% between 2013 and 2039 (U.S. Energy Information Administration, 2013). Whether the price will increase proportionally is difficult to say, as this depends partly on the current expansion of shale gas production and partly on the scarcity of other energy sources.

Clearly, developments in GM soya could potentially lead to a very large disruption in the supply of animal feed, and therewith to a large increase in legume crops in Europe. However, if the policies of the EU and its member states towards genetic modification would become more tolerant (for instance by establishing thresholds for the low-level presence of non-certified varieties in shipments, or by accepting GM varieties approved by exporting countries), then such a scenario will not come to pass. Still, the scenario shows what may happen as a result of autonomous developments.

Modelling a policy for forage legumes is difficult in CAPRI, because they are not included in the model as distinct crops. The tests reported here were done with clover in grassland, so a policy to increase that proportion was designed. By definition, this will lead to a significant increase in legumes. It will increase the production cost for most livestock farmers (at least initially), but against that stand environmental benefits, most notably those associated with reduced use of synthetic nitrogen fertiliser.

Greenhouse gas mitigation costs

The Marginal Abatement Cost Curve approach was used to analyse the costs of greenhouse gas mitigation using legumes in European farming systems (Moran, 2010). An analysis of increasing the share of legumes in rotations in the five Legume Futures study areas in Europe (Calabria, Western Sweden, NE Scotland, Brandenburg and Romania) can bring significant benefits in GHG mitigation, potentially providing financial savings to farmers and increasing the total DM production in these areas. To achieve a cost-effective abatement of 0.7 – 0.9 Mt CO_{2eq} (13% of the soil N_2O emissions from these land areas), grain legumes and fodder legumes (including grass-legume mixtures) should be cultivated on around 15% and 10% of the arable land areas, replacing overall 25% of the non-leguminous fodder and cereal areas. Though the increased cultivation of legumes would reduce cereal production, it would provide additional proteins both for animal and human consumption, reducing the need for feed protein imports and possibly animal protein consumption (the grain legume production was 1.2-1.8 Mt DM at the cost-efficient abatement, this accounts to 4.9-5.5% of the 34.4 Mt DM/y soybean import to the EU-25). The reduced cereal production would have implications on cereal production elsewhere, potentially resulting in a GHG leakage. The overall impact of such a shift in the place of production needs a life cycle analysis approach.

The results of this study demonstrate that the wider cultivation of legumes within European farming systems could deliver the twin outcomes of improved economic performance in reduced GHG emissions, thereby contributing to policy targets for GHG mitigation without threatening food security or farm incomes.

Costs and benefits

Based on an assessment of those costs and benefits that can be quantified, we can compute at a tentative value per hectare for the two standards set: in arable agriculture, a value for a rotation consisting of one year faba bean followed by three years wheat as compared to four years wheat alone; and in pasture-based farming, modestly fertilised grassland with 25% clover as compared to conventional grassland (see also Legume Futures Report 4.6). The result is shown in Table 10.

Table 10. Overview of costs and benefits of two legume-supported agricultural systems.

		faba bean/wheat			grass/clover		
Environmental impact (benefit +, cost -)	*unit per ha*	*quantity*	*price*	*value*	*quantity*	*price*	*value*
Reduction of greenhouse gas emissions	t CO_{2e}	1.975	€18-72	€36-142	1.347	€18/72	€24-97
Reduction in eutrophication	kg N_r	-30 to +7	€3	-€90 to +€21	39	€3	€117
Reduction in ammonia emissions	kg NH_3	13.5	€3.3	€44	15-30	€3.3	€49-98
Reduction in NO_x emissions	kg N_r	0.19	€2.7	€0.51	0.003	€2.7	€0.08
Phosphorus mobilisation	kg P_2O_5	7.6	€0.38	€2.86	4.5	€0.38	€1.69
Reduction in soil erosion and pesticide use, increase in biodiversity				p.m.			p.m.
total environmental effects				-€7 to +€210			€192-314
cost to farmer							
gross margin				-€50			-€400

A few preliminary conclusions can be drawn from these figures, rough as they may be.

The environmental benefits of clover on grassland are larger than those of grain legumes on arable land. However, the cost to the farmer is also higher.

If we take the most favourable scenario, i.e. where we use the carbon price calculated in the Stern Review (Stern 2007) and we assume that excess leaching of nitrate from legume fields can be avoided by appropriate crop management, the environmental benefits are much higher than the average loss to the farmer.

However, bearing in mind that the range in gross margins from grain legumes is very large, this will vary highly by region and by crop.

If, on the other hand, we use the much lower carbon price proposed by the IMF and if we accept that nitrate leaching will be problematic, the calculated environmental effects from rotations with grain legumes may be too low to justify special incentives for growing legumes on arable land. It must be borne in mind that we have not quantified all environmental effects, so the net figure of -€57 per hectare is not an indication of the overall social benefit of rotations with legumes, but rather the cost of promoting biodiversity and a healthy soil. Whether these benefits are worth that price is a question that cannot be answered with the figures at our disposal.

For forage legumes, the price of providing said benefits appears to be higher: of the order of €100-200 per hectare.

For grain legumes, the largest environmental benefit seems to be the climate mitigation effect – at least as far as quantifiable benefits go. This is the case even if we use the lower of the two carbon prices. It is different for forage legumes, however, or at least for clover on grassland: the climate mitigation effect is lower here. In part this is because we assume that even with a significant proportion of clover the grassland will still be fairly heavily fertilised – at least with organic manure, leading to N_2O emissions.

On the other hand, eutrophication will be significantly lower in grass-clover swards compared to conventional grassland: not only is fertiliser applied in somewhat smaller quantities, but there is no crop residue ploughed into the soil as on arable land. Also, ammonia emissions are reduced, leading to less acidification.

As was perhaps to be expected, the effect of phosphorus mobilisation is modest. However, it may be questioned whether the market price of phosphate adequately represents its value, partly because of the expected shortage of phosphate rock in the foreseeable future and partly because of the long-term effect of P fertilisation and P presence in the soil.

Both environmental and farm-economy effects have long-term as well as immediate aspects. For instance, the buildup of carbon in the soil is cumulative, meaning that as the organic matter content rises it will only generate major effects after a number of years. On the other hand, the increase in soil carbon is likely to level off after some time. Similarly, some of the improvements achieved by growing legumes (higher biodiversity, less soil erosion) will also lead to higher yields, but only in the longer term. Whether this is sufficiently attractive to the farmer depends on the latter's perspective on time, hence on the discount ratio. That ratio is incorporated into the price of carbon used here (particularly in the higher price), but not in the prices of the other environmental effects.

THE EUROPEAN LEGUME RESOURCES CENTRE

Pete Iannetta, JHI, UK

The European Legume Resource Centre (or ELRC), was established by the Legume Futures project and is accessed at www.elrc.eu.

The ELRC is an information centre designed to facilitate research and development of legume supported cropped systems. The ELRC website is available for upload and download of material by Legume Futures members and any other legume scientists or technologists who contact the webmaster (pete.iannetta@hutton.ac.uk).

Simple guides and templates have been made available online to facilitate preparation of entries and data for upload. Also, the content is flexible and we welcome contributions and suggestions from colleagues.

A main aim of the ELRC is to empower future research on legumes and their symbionts and their main defining attribute: the fixation of atmosphere nitrogen into biologically useful forms.

Among the resources currently presented on the ELRC is a simplified guide for scientists wishing to use a key methodology to quantify nitrogen fixation by legumes called the '*^{15}N Natural Abundance technique*', developed from the publications of, and in consultation with Murray Unkovich (Unkovich et al. 2008). The %Ndfa (the proportion of nitrogen derived from air), by legumes is estimated only rarely and usually under highly controlled experimental conditions. Similarly, this proportion should be translated to estimate biological nitrogen fixation in absolute terms, and this demands a measure of root contributions too - which are also usually only estimated. More measurements of %Ndfa and biological nitrogen fixation are required in field, and across a more diverse range of countries/environments.

Similarly, there is a need to generate a bank of rhizobial isolates for cropped legumes: from which we should identify elite strains - that can fix high level of nitrogen having been able to persist in field and compete with other strains to nodulate (testing their ability to fulfil 'Koch's Postulates').

Thus, key methodologies and features of the ELRC include:

- A standard operating procedures to isolate rhizobial isolates and characterise their genetic diversity. This will include specific methods for genetic characterisation of *Rhizobium leguminosarum* bv. viceae (nodulators of *Vicia*, *Pisum* and *Lathyrus* spps.)

- Legume supported crop system design principles, guidance and aids. This is a critical addition to the ELRC and it will enable system designers using the principles and associated Dexi tree and MADM (Multi-Attribute Decision Aid Model), software for their own legume based cropping scenarios. The ELRC will incorporate a facility for users to download the outputs of the scenarios they test - for comparative purposes.

- Soil surface N-budget calculation - a collaborative service facility available from the James Hutton Institute that enable rapid calculation of N budgets from agronomic patch, field or farm level data (

- A paper detailing the findings of the Legume Futures Stakeholder Group Meeting (2014).

- Legume Group Meeting Minutes (UK - annual meeting 2013) and links to other Legume societies and meeting minutes (2015).

- Germbanks - in the first instance these will detail Rhizobial isolates held at the James Hutton Institute.

- A faba bean collection.

- Free downloadable Legume Futures web banner and logo.

- The legume futures database (from March 2015): https://sigmea.scri.ac.uk/legume/, is currently for members only. It will become publically available on request from the curator, mark.young@hutton.ac.uk. This will allow users to use the historical datasets and upload their own of N-budget datasets. To encourage the latter, this facility shall be linked to the 'soil surface N-budget' service (detailed above).

- A report on new and emerging legume-based copping services and technologies. For example: the lunch of a new service facility based at the James Hutton Institute that aims to serve legume growers. This will estimate nitrogen fixation in legume crops and assess soil quality including rhizobial diversity. In addition, this service will provide advice on remedial actions and interventions as appropriate.

LEGUME FUTURES: AN IMPACT ASSESSMENT

Donal Murphy-Bokern, Germany

The aim of Legume Futures was to deliver the knowledge base that will support the role of legumes in the sustainable development of European farming systems. Early in the project we identified 10 practical outcomes that further this. These are:

Agricultural, economic, environmental outcomes

Increased production of legume crops with higher yields.
Reduced use of synthetic nitrogen fertiliser.
More diverse rotations including legumes.
Increased use of European legumes in animal feeding.

Scientific impact and dissemination

Raised awareness in society/policy community.
Cooperation in supply chains.
Scientific publications for impact, QA and recognition.
Scientific publicity for recognition, profile and sustained investment.
Education for legacy.
Better access to enriched knowledge resources.

To support these outcomes the project tasks (Figure 18) have produced the following key outputs:

Case studies.
Environmental assessments.
Socio-economic assessments.
Resource use assessments.
Policy assessments.
Review of non-food and novel uses.

The impact of Legume Futures depends on the communication of these outputs to primary users and their response in terms of changes to public policy and farm-level innovation. The first communication plan developed in the first year of the project identified 15 communications activities, products and media. As the project progressed, this was focused down to ten activities:

Legume Futures reports
Local Stakeholder Fora
The European Legume Resources Centre
The knowledge and technology review
The Legume Futures book
The Legume Futures website
Project newsletters
Peer-reviewed scientific papers
Conference contributions
The project general report

Primary publication of research and management of intellectual property

Figure 18 was drawn on the basis of the commitments set out in the Description of Work and on the primary publication activities partners.

Our principal research output is knowledge and understanding to enable changes in farming systems so we aimed to provide maximum open access to our research processes, resources and results. So we have deliberately avoided embedding specific commercial interests in our research. We are independent and free to publish all outputs by default. This is central to our approach to maximising the uptake and exploitation of the intellectual property produced. Our approach to publication also considered that project reporting should properly report to the public rather than confuse reporting for internal auditing purposes with publication. Arising from this, those project reporting documents that have a public character are prepared as monographs to fully record the work in the public domain. This applies particularly this general project report and the supporting Legume Futures Reports.

These published outputs have been prepared using a project identity and standard presentation guidelines presented at the project kick-off meeting. All partners were encouraged to prepare publication materials to this high standard and were supported in doing so. This has given the projects direct outputs (reports, presentations and the project website (www.legumefutures.de) a consistent and unified appearance, with particular emphasis on clear presentation of information consistent with international publication standards.

Legume Futures reports
The research results are published primarily through the project website and through conventional academic publications. Fourteen Legume Futures reports have been

prepared directly from the research tasks and contract deliverables that have a public character. These are project monographs that provide a full account of the research process and results in particular areas. They allow the research results to be integrated and presented in relation to users' perspectives rather than fragmented according to conventional academic reporting.

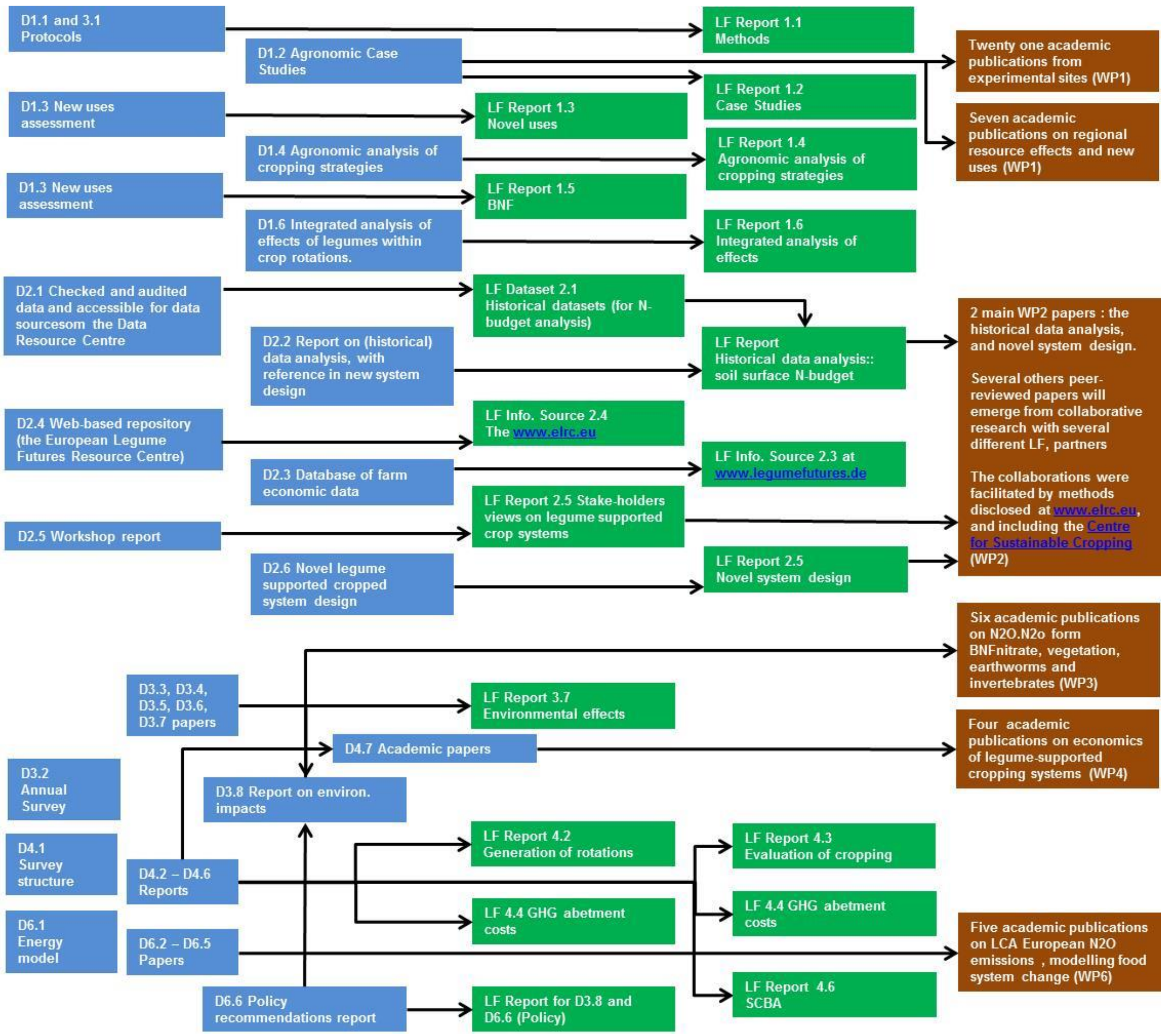

Figure 18. Links between contract deliverables (blue boxes) and primary publications (Legume Futures reports (green boxes) and academic papers (brown boxes).

Table 11. The titles of the 14 Legume Futures reports.

Report number	Title	Report number	Title
1.1	Sampling and measurement protocols for field experiments assessing the performance of legume-supported cropping systems.	2.4	Report on novel system design
1.2	The case studies of participant expertise in Legume Futures.	3.8/6.6	Policy implications of the environmental and resource effects of legume cropping.
1.3	Novel feed and non-food uses of legumes.	4.2	Generation and evaluation of legume-supported crop rotations in five case study regions across Europe (to be published later).
1.4	Agronomic analysis of cropping strategies for each agroclimatic region.	4.3	Evaluation of legume-based agriculture and policies at farm level.
1.5	Integrated analysis of biological nitrogen fixation (BNF) in Europe.	4.4	Greenhouse gas abatement costs of introducing legumes into cropping systems.
1.6	Integrated analysis of effects of legumes within crop rotations (to be published later).	4.5	Impacts of legume scenarios.
3.7	Environmental implications of legume cropping.	4.6	Social Cost-Benefit Analysis of including legumes in cropping systems.
2.2	Report on historical data analysis	5.3	Outlook for knowledge and technology for legume-supported cropping systems.

Peer-reviewed scientific papers

At the time of writing this report, the Legume Futures consortium has published 23 peer-reviewed academic papers, submitted a further 2, and was preparing a further 31 papers. Overall, we are confident that the project will yield between 50 and 60 academic journal articles.

Secondary communications

The consortium has engaged in a wide range of secondary communications to complement formal scientific publication. The overall aim is to further a wide range of impacts in a diverse stakeholder community. These communication activities were focused on the key policy and technical changes required to enable legumes to contribute optimally to European agriculture. These are summarized as follows:

The knowledge and technology review

Based partly on the results of intensive stakeholder engagement activities and on review of the literature, the knowledge and technology review (Murphy et al. 2014, Legume Futures Report 5.3) sets out thoughts from the consortium on the challenges of increasing the production of legume crops in Europe and the potential approaches to research and development that might be taken. Much of the review of the literature presented draws heavily on work that consortium members did for the European Parliament in 2012 and 2013 (Bues et al. 2013).

The Legume Futures book

The Legume Futures book is an important deliverable of the Legume Futures project. The primary purpose is to present the broader cropping systems context behind the Legume Futures project. Twenty three chapters are being prepared, with several from authors outside the consortium. Chapters from consortium members will draw on project results but also set that in a wider context. The book is aimed at professional intermediaries, teachers, students, other. It will be published by CABI and we have made arrangements for it to available through open access as an e-book one year after its initial publication. The book is a major undertaking and will be more than 200 pages providing a comprehensive over-view of the development of legume-supported cropping systems.

Project newsletters

These are largely project internal updates but that are publicly available on the project website.

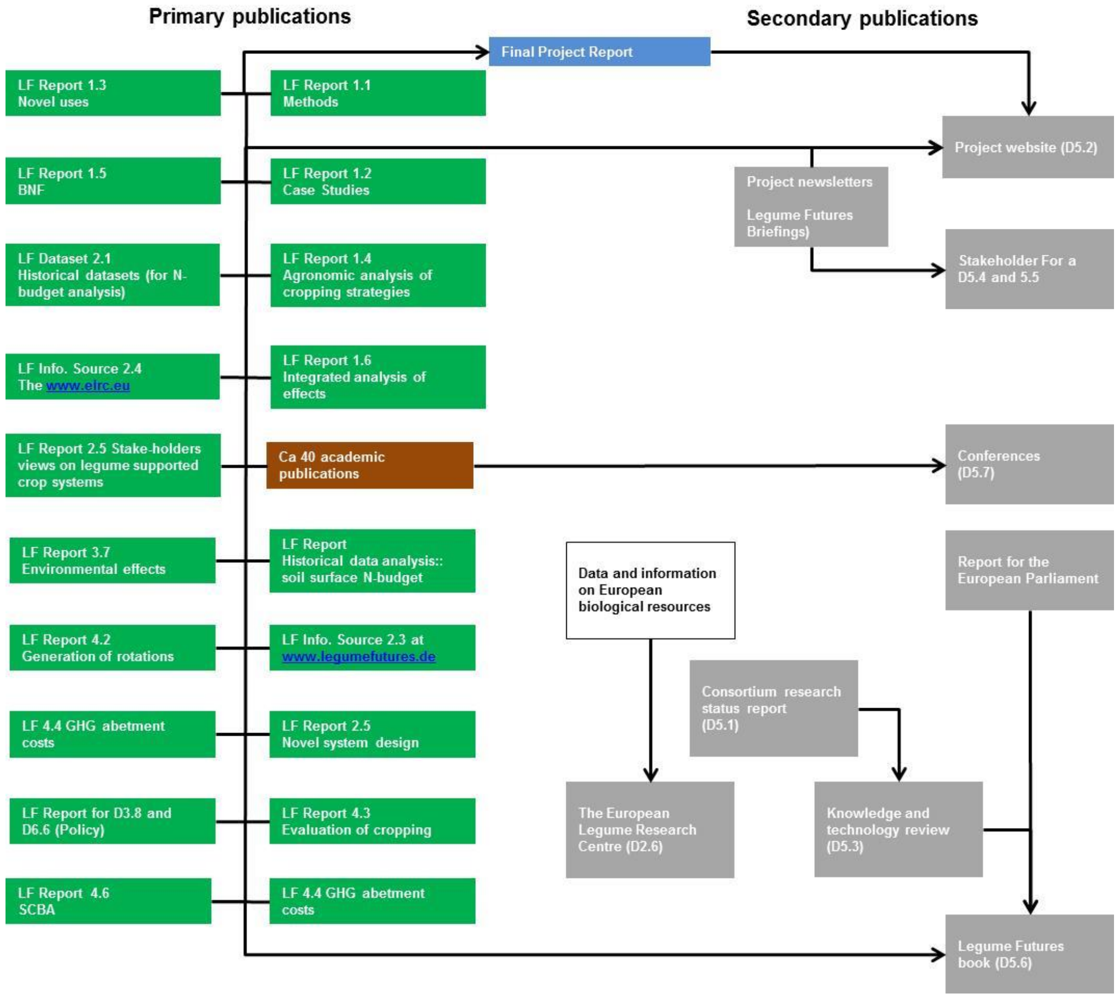

Figure 19. Relationships between primary and secondary publication activities in Legume Futures

Local Stakeholder Fora

Fifteen Local Stakeholder Fora were formed (Table 12). The main purpose was to access the insights of local users as input into the research process. These were largely based on existing interactions between site-based partners and local stakeholders. Two of these engage with cross-European groups – one on interactions with policy makers in Europe and one based on interactions with the German Agricultural Research Alliance (DAFA).

A survey of the site-based (farm) LSF conducted in 2013 and 2014 indicated that these have interacted with about 700 stakeholders across the 13 sites involved. In addition, the work with DAFA involved intensive interaction with about 100 private sector stakeholders in Germany. The insights gathered by partners through these interactions flowed into results and reports (for example Legume Futures Report 1.2 (Stoddard et al. 2013) which in turn has influenced the consortium's view of development challenges.

The survey of the LSF conducted in 2013 indicates that the project has used and strengthened interactions between the Legume Futures experimental sites and local stakeholders significantly and that in many cases this will continue after Legume Futures ends. There is therefore a legacy of increased awareness of local contexts, challenges and users' perspectives in the research team. In addition, some of this stakeholder interaction was conducted to inform future research activities (DAFA and the EIP) and so Legume Futures will have a significant legacy arising from its contribution to future research plans.

Table 12. Details of the 13 Local Stakeholder Fora established by partners with sites for field experiments.

Local Stakeholder Fora	Partner	Country	Contact
The Aarhus Legumes Forum	AU	Denmark	Kirsten Schelde
The Calabrian Legumes Forum	UDM	Italy	Michele Monti
The Crotalaria Futures Forum	CIRAD	France	Phillipe De Lajudie
The Dundee Legumes Forum	JHI	UK	Cathy Hawes
The Edinburgh Legumes Forum	SRUC	UK	Valentini Pappa
LEGUMESHellas	AUA	Greece	Dimitrios Savvas
The Polish Lupin Society	IUNG-PIB	Poland	Jaroslaw Stangenga
The ProAgria Legumes Forum	HU	Finland	Fred Stoddard
The SLU Forage Legume Forum	SLU	Sweden	B. Frankow-Lindberg
The SLU Grain Legumes Forum	SLU	Sweden	G. Bergkvist
The Teagasc Clover Group	Teagasc	Ireland	James Humphreys
The TilaTesti Legumes Forum	MTT	Finland	Riitta Lemola
The Trendhorst Legumes Forum	vTI	Germany	Herwart Boehm

The survey of the site-based LSF yielded the following insights (summarised):

Eight of the 13 LSF were based on existing interaction with local stakeholders. The project stimulated four partners to initiate stakeholder interactions. All relevant partners indicated that these interactions will continue after the project ends. Three reported that the LSF influenced the research in the project and six partners indicated that their LSF provided valuable insights and ideas for new research.

Most partners reported an increase in the importance of using legumes for provisioning (ecosystem) services in the recent past and all LSF except one report that the importance of legumes for provisioning services is expected to increase in the future. A similar pattern is evident for regulating and supporting services. They report in particular a switch in thinking from the past to the future with regard to supporting services. This means that many of the stakeholders we have been interacting with predict an increase in emphasis in supporting services (e.g. soil protection and fertility).

All LSF except one (Teagasc Clover Group) see policy intervention to complement market effects as necessary to increase the use of legumes. Three of these see change as largely dependent on public policy intervention. This is a significant message from 13 groups of stakeholders across Europe.

Turning to adoption, the survey revealed that the project is usually regarded as directly relevant to small numbers of farmers around the case study sites. Several of the sites are clearly focused on niche systems such as organic systems, one (the Crotalaria Futures Forum is focused on a specialised use. These indicate that the impact on these is in-direct, but widespread and significant. In assessing this, it is important to remember that these LSF are focused on farm practice and most of them will not have been focused on the relevance of the project to public policy – which they see as critical to the future of the legume production.

Six of the 13 LSF groups report that the project will have significant impact on them, with three reporting that this impact will be indirect and widespread.

Strategic stakeholder forum
These interactions with users was complemented by a Strategic Stakeholder Forum that provided strategic advice on user needs. The members were:

Prof. Trond Storebakken, University of Norway.
Mr Wilfrid Legg, Former Head of Policies and Environment Division, OECD.
Mr Ole Groenbaek, DFL-Trifolium A/S, Denmark.
Mr Richard Perkins, WWF International.
Mr Ron Stobart, NIAB, UK

The Strategic Stakeholder Forum was light-handed in advising on our communications activities providing valuable guidance on certain aspects, for example the advice to avoid being dragged into any anti-soy debate that has anti-trade implications. They highlighted early on the difficulty in getting direct access to agri-business interests and this motivated the project's intensive involvement in the DAFA German stakeholder interaction process.

The farm supply sector responds to the demand from farmers for seeds etc. while the post-farm food and feed sector is focused on commodity trading. We were advised that that the commercial animal feed sector has no direct interest in promoting the replacement of imported soy with European-grown legumes. This insight was confirmed by subsequent involvement in stakeholder interactions, particularly through the DAFA and the the EIP Protein Crops Focus Group that included partners DMB and UH.

Policy-makers workshops
Legume Futures has already engaged directly with policy-makers with a presentation to staff at DG Agri. in Brussels on 30 June 2011 and to members of the European Parliament on 30 May 2012. In addition, several partners presented a report to the European Parliament in April 2013 (from review work funded by the Parliament).

The Legume Futures website
A project domain name (www.legumefutures.de) accesses the project website that is provided by DMB. The purpose of the Legume Futures website is that of a conventional EU project website providing a wide range of users with data, information, knowledge and insight into the project, its partners, the research work, and its results. The site is being maintained and updated for five years after the project close – i.e. until 2019.

Conference contributions
All partners were active at conferences. The project has played a leading role in organising three international meetings: The Nitrogen and Global Change conference in Edinburgh in 2011, the Association of Applied Biologists meeting on “Making crop rotations fit for the future” in Newcastle in December 2011, and the Congress of the European Society of Agronomy in Helsinki in August 2012. There were 8 presentations and 13 posters from Legume Futures at the 2012 ESA congress. The project also featured at the 2014 ESA congress in August 2014.

At the end of the project when all results have been analysed, a standard Legume Futures presentation, or a set of presentations, will be prepared to enable all partners to present the wider project results to a wide range of audiences over the two years following completion.

Integrated assessment of project impact

The primary purpose of Legume Futures is to support the sustainable development of European agriculture. The delivery of this impact through innovation in farm practice is ultimately dependent on the decisions made by many thousands of farmers in Europe over years and decades to come. Beyond this primary target, there are also impacts on the environment, science, education and the European Research Area. Here we provide an integrated assessment of the impact of Legume Futures in relation to these five areas.

Sustainable development of agriculture

Legume Futures focuses on three main routes to innovation in agricultural practice: agricultural policy; on-farm technical change in the short term; and supporting technical change in the longer term. This impact area is entirely dependent on the decisions of farmers influenced by public policy, and technical (or market) opportunities (Fig. 20). Legume Futures has addressed both.

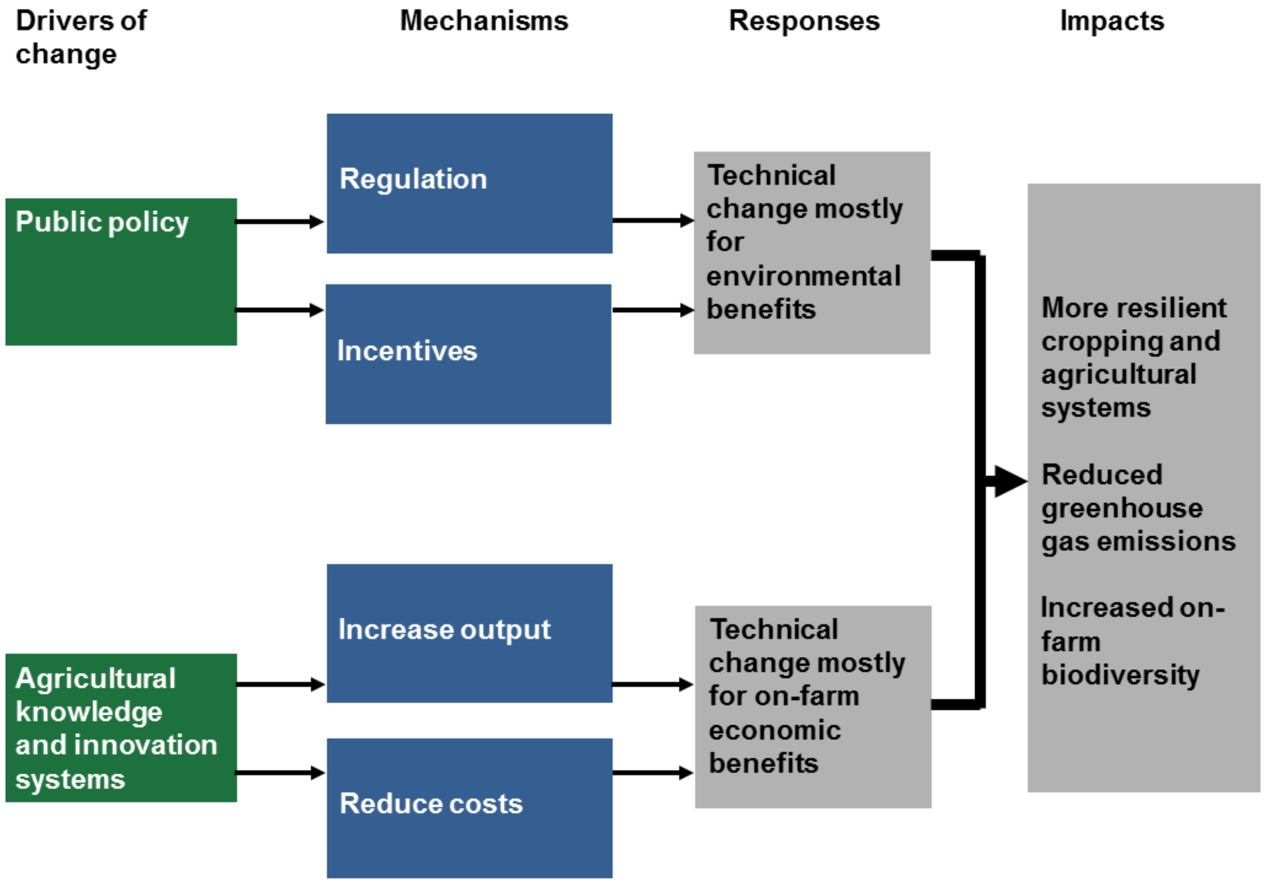

Figure 20. Drivers, pathways and impacts of optimising European cropping systems using legumes.

Through public policy: The Legume Futures project coincided with the negotiations leading to the reform of the Common Agricultural Policy to operate up to 2020. Even though few results of the primary research were available, the Legume Futures consortium (esp. DMB, SRUC, WUR, JHI, UH and ZALF) interacted intensively with the relevant European policy community, particularly the European Parliament, The European Commission, the German Government (through the German Agricultural Research Alliance (DAFA), and members of the wider policy community at EU level. The integration of the review conducted for the European Parliament (as a separately funded project) and the Legume Futures project was instrumental in this. In addition to related reports, several public presentations were made, some highly focused on key players in the policy community. We also attended to the wider policy-science interface in this area through the UNECE Task Force for Reactive Nitrogen. This interaction was important in putting the effect of expansion of legumes into a wider land-use and nitrogen cycle perspective (Westhoek et al. 2014). Our work on bridging agronomic research and policy included the coordination of a statement from the European Society of Agronomy on CAP reform ('greening').

The Legume Futures collaboration was instrumental in supporting the public debate about the use of legumes to improve the environmental performance of European crop production. Our research confirmed that public policy intervention to support the increased use of legumes is justified. We are confident that we were instrumental in establishing consensus in the European policy community with respect to supporting the expansion of legume production. The overall effect of the public debate was the qualification of legume crops as Ecological Focus Areas and the option to introduce or maintain coupled payments. There are also regional initiatives supporting legume production, particularly in Germany. At the time Legume Futures ended, CAP reform details affecting the use of legumes were still under discussion. However, it is clear that there is consensus in the policy community that an increase in the use of legumes would bring a wide range of public and private benefits.

Through the private sector: The ultimate impact of Legume Futures depends on the actions of millions of farmers. With respect to the private sector, the purpose of interactions with farmers and others in the supply chain was to ensure that Legume Futures research was conducted with insights into the contexts in which the research will be used. The research has identified novel cropping sequences that can use legumes to increase farm-level profitability. The research has also quantified the farm-level gross margin deficits in five regional case studies. This provides a foundation for local and regional research focused on optimising legume-supported cropping systems in specific farming contexts.

Legume Futures did not aim to extend its results to farmers directly.

Considering that this is a medium-sized project focused on strategic research questions (rather than applied questions), there has been substantial interaction with private sector stakeholders complementing the intense interaction with the public sector. The survey of the LSF conducted in 2013 and 2014 indicated that these have interacted with about 700 stakeholders across the 13 sites involved. In addition, the work with DAFA involved intensive interaction with about 100 private sector stakeholders in Germany. All plans for communications were subject to scrutiny from the Strategic Stakeholder Forum. The insights gathered by partners through these interactions flowed into results and reports (for example Legume Futures Report 1.2, Agronomic Case Studies, Stoddard et al. 2013) which in turn has influenced the consortium's view of development challenges.

The survey of the LSF conducted in 2013 indicates that the project has used and strengthened interactions between the Legume Futures experimental sites and local stakeholders significantly and that in many cases this will continue after Legume Futures ends. There is therefore a legacy of increased awareness of local contexts, challenges and users' perspectives in the research team. In addition, some of this stakeholder interaction was conducted to inform future research activities (DAFA and the EIP) and so Legume Futures will have a significant legacy arising from its contribution to future research plans.

Environmental impact

Our environmental assessments provide the foundation of the project's environmental impact, which is dependent largely on public policy. The research is also relevant to private sector measures, for example with corporate responsibility which is expanding rapidly in the agri-food sector.

For both approaches, our research shows that legume crops have multiple positive environmental and resource-conserving effects operating at field, farm, regional and global levels. These effects point to the need to recognise the potential of complementary policy measures and to foster efforts to enhance this complementarity. Such an integrated policy approach can be particularly robust if it focuses on the positive outcomes that legume crops can bring about for society. To make them complementary to one another, measures should be rooted in an understanding of the agroecological processes governing the benefits.

With the current low use of legume crops, the promotion of legumes through greening measures can be justified by environmental benefits from a practical policy viewpoint. Combined with investment in research and development, this could stimulate private-sector investment in crop improvement and technical progress. This private investment in technical change is important because the current minority status of protein crops in Europe is determined largely by the yield advantage of carbohydrate-rich cereals. This means that in the long term, a closing of the yield gap between protein crops and cereals, particularly in terms of protein yield, is an important strategic goal. There is also a need to improve the ability to capture for farmers the on-farm economic benefits of more diverse rotations that include legumes.

Science

Up until the end of 2014, the Legume Futures consortium members published 26 articles in peer-reviewed academic journals and are in the process of preparing a further 33 from the results. In addition, consortium members made 91 oral presentations and 37 poster presentations to scientific meetings with 30 published articles in conference proceedings. A total of 340 dissemination activities are listed in the register of project outputs.

Education

The project has directly supported four doctoral students.

In addition to this substantial investment in post-graduate education, the project has also supported educational activities at the vTI in Germany and CIRAD in France.

In the longer term, the Legume Futures book is particularly relevant in the education community, but also to all involved in developing cropping systems.

European Research Area

Particularly in the first two project years, Legume Futures was one of only a few international collaborative research projects relevant to the development of cropping systems operating at the time. The collaboration initially brought together 20 partner organisations. Sixteen of these were and still are running long-term cropping system experiments relevant to the development of legume-supported cropping systems. The success of the project in fostering a common understanding of the challenges and opportunities in developing cropping systems is a significant achievement and contribution to the European Research Area. This achievement is under-scored by the request in 2012 from The University of Novi Sad (Serbia) to join the consortium on a self-funded basis. In addition, the work on the Legume Futures Book attracted additional contributions from five further organisations including the Swedish Institute of Agricultural Engineering and INRA in France.

The collaboration brought together four main types of researchers: agronomists running field experiments; researchers focused on environmental processes; modellers; and economists and specialists in policy development. The resulting interactions will have a lasting effect and in particular brings a lasting wider systems and policy perspective to the conduct of the relevant agricultural field experiments. All consortium meetings included trans-disciplinary discussions about the wider challenges of developing cropping systems.

On research policy, Legume Futures engaged in detailed discussions about legume research needs with German stakeholders organised by the German Agricultural Research Alliance (DAFA). Legume Futures was instrumental in the preparation of the DAFA research strategy for legumes. In relation to European research policy, two members of the consortium (Fred Stoddard (UH) and Donal Murphy-Bokern) have been selected by the EC to serve on the European Innovation Partnership Focus Group on protein crops. This group started in September 2013 and advised the EC on investment in legume crops R&D. We also responded in detail to consultations about the development of research policy on the 'bioeconomy'.

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APPENDIX 1

Supplementary Table

Sources of constants reported in Table 3.

	Beans	Faba bean	Chick-pea	Lentil	Lupins	Pea	Soya bean	Vetches
Grain protein content	1	1, 2	1	1	1, 2	1, 2	1, 3	4
Harvest index	7, 8, 9, 10, 11	12, 13, 14	15, 16	17	18, 19	20, 21, 22	23	4, 24
N harvest index	8	25, 26, 27	27, 28	28	29	30, 31	3	4, 32
Root:shoot ratio	33, 34	19, 35, 36, 37	38	39	19	31, 40, 41, 42	43, 44	32, 45
Root N content	33, 46	47,48	28	28	49	50, 51	23	32,52
Proportional rhizodeposition[b]	53, 54	54	27, 54	53, 54	54	21, 31, 54	55	53, 54
Ndfa	56, 57	58, 59	59, 60	59, 61, 62, 63, 64, 65	66	58, 59	3, 60, 23, 67	68, 69

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APPENDIX 2

List of publications (13.1.2015)

Year	Title	Journal	Vol.	Pages	Lead Legume Futures author	Lead partner organisation
2010	Emissions of nitrous oxide from arable organic and conventional cropping systems on two soil types	Agriculture, Ecosystems & Environment	136	199-208	Chirinda, N.	AU
2011	Tillage system effect on nitrogen rhizodeposited by faba bean and chickpea	Field Crops Research	120	185-195	López-Bellido, L.	UCO
2011	Chickpea and faba bean nitrogen fixation in a Mediterranean rainfed Vertisol: Effect of the tillage system	European Journal of Agronomy	34	222-230	López-Bellido, R.J.	UCO
2011	Faba bean root growth in a Vertisol: Tillage effects	Field Crops Research	120	338-344	Muñoz-Romeo, V.	UCO
2011	Long-term effect of tillage, rotation and nitrogen fertiliser on soil quality in a Mediterranean Vertisol	Soil & Tillage Research	114	97-107	Melero S.	UCO
2011	Nitrous oxide emissions and nitrate leaching in an arable rotation resulting from the presence of an intercrop	Agriculture, Ecosystems & Environment	141	153-161	Pappa V A	SRUC
2011	Cereal yield and quality as affected by N availability in organic and conventional crop rotations in Denmark: a combined modeling and experimental approach	European Journal of Agronomy	34	83-95	Doltra, J.	AU
2012	Stratification ratios in a rainfed Mediterranean Vertisol in wheat under differenttillage, rotation and N fertilisation rates	Soil & Tillage Research	119	7-12	Melero S.	UCO
2012	The effects of the tillage system on chickpea root growth	Field Crops Research	128	76-81	Muñoz-Romeo, V.	UCO
2012	Wheat response to nitrogen splitting applied to a Vertisols in different tillage systems and cropping rotations under typical Mediterranean climatic conditions	European Journal of Agronomy	43	24-32	López-Bellido, L.	UCO
2012	Intercropping: effect on yield and N balances in a three year crop rotation.	The Journal of Agricultural Science	150	584-594	Pappa V A	SRUC
2012	N2-fixation and residual effect of four legume species and four companion grass species	European Journal of Agronomy	36	66-74	Rasmussen, J.	AU
2013	Chickpea water use efficiency as affected by tillage in rainfedMediterranean conditions	Agricultural Water Management	129	194-199	Fernández-García, P.	UCO
2013	Nitrate accumulation in the soil profile: Long-term effects of tillage, rotation and N rate in a Mediterranean Vertisol	Soil & Tillage Research	130	18-23	López-Bellido, L.	UCO
2013	The role of catch crops in the ecological intensification of spring cereals in organic farming under Nordic climate	European Journal of Agronomy	44	98-108	Doltra, J.	AU
2013	Sources of nitrogen for winter wheat in organic cropping systems	Soil Sci.Soc.Am. J.	77	155-165	Petersen, S.O.	AU
2013	Complementary effects of red clover inclusion in ryegrass/white clover swards for grazing and cutting	Grass and Forage Science	>68	(1-10)	Eriksen, J.	AU

2013	Effects of grass-clover management and cover crops on nitrogen cycling and nitrous oxide emissions in a stockless organic crop rotation	Agriculture, Ecosystems & Environment	181	115-126	Brozyna, M.A	AU
2013	Chemical and biological responses in a Mediterranean sandy clay loam soil under grain legume-barley intercropping.	Agrochimica	57	1-21	Tortorella D.	UDM
2014	Food choices, health and environment: effects of cutting Europe's meat and dairy intake	Global Environmental Change	26	196-205	Murphy-Bokern, D	DMB
2014	Inter-annual variation in nitrous oxide emissions from perennial ryegrass/white clover grassland used for dairy production.	Global Change Biology	20 (10)	3137-3146	Burchill, W.	Teagasc
2014	Effects of fertilization and salinity on weed flora in common bean (Phaseolus vulgaris L.) grown following organic or conventional practices	Australian Journal of Crop Science	8(2)	178-182	Bilalis D.	AUA
2014	Effects of contrasting catch crops on nitrogen availability and nitrous oxide emissions in an organic cropping system	Agriculture, Ecosystems & Environment	199	382-393	Olesen, J.E.	AU