Summary

This document presents the role of legumes used in agriculture: grains, vegetables, forage legumes and for forestry or coppice and suggests research priorities in crop and model systems.

- Nitrogen fixation by legumes allows them to reduce the energy costs of agriculture and to minimise greenhouse gas production.
- Legumes provide healthy protein sources both for food and livestock feed.
- Legumes contribute to biodiversity in agriculture, in pasture ad in field crop rotations.
- Certain legume shrubs are ideal for land reclamation and others can be the basis of sustainable forestry and biomass production

The main challenge to legume research is to determine how, once integrated into sustainable farming systems, their profitability can be optimised for the farmer while maintaining their environmental benefit.

Two major linked research areas emerge from this challenge:

i. how can these crops best be improved and managed for maximal productivity and minimal environmental impact

ii. how the quality of products: food, feed, fodder, or fuel can be improved or maintained with increasing production efficiency, or be tailored to specific end uses.

Background:
The nitrogen cycle contributes substantially to the environmental impact of agriculture. This involves energy demand, greenhouse gas production and directly through water pollution. Legumes have a unique role in the nitrogen economy of agriculture and to moderate the environmental impact of agriculture it is necessary to understand how legumes should best be deployed in agricultural systems.

Agriculture requires access to assimilable nitrogen. Mostly this is provided from soil and a proportion is removed in harvested material. The amount of nitrogen available to a crop is a large determinant of its yield, so nitrogen is typically supplied to crops in the form of inorganic fertiliser or recycled manure. The production of inorganic nitrogen fertiliser requires a great deal of energy, as does its distribution and application; the synthesis, transport and spreading of one ton of nitrogen fertiliser needs approximately one ton of fossil fuel. Annual inorganic nitrogen fertilizer use world wide amounts to approximately 80Mt, so the energy demand associated with nitrogen fertilizer use corresponds to a considerable consumption of fossil fuels and production of greenhouse gases.

Legumes are unique among crops because they can establish a symbiosis with nitrogen-fixing soil bacteria, turning atmospheric nitrogen into a biologically useable form. This symbiosis is estimated to fix as much nitrogen every year, as the fertilizer industry worldwide and so plays a considerable role in agriculture as well as in natural ecosystems. Legume crops can annually fix between 100 and 400 kg of nitrogen per hectare. This is available to the legume crop obviating the need for fertilizer and the nitrogen fixed by the crop not removed at harvest is available for the following crop either reducing or obviating the need for subsequent fertilizer application.

In pasture, animals feed on a mixture of grass and a legume, the latter having a high content protein in its leaves. The mixture of a grass and a legume is efficient for both components as the legume does not compete with the grass for soil nitrogen and the depletion of soil nitrogen by the grass improves the fixation efficiency of the legume. For example, clover fixes 300-400 kg of nitrogen per ha when associated to grass. This principle is also employed in intercrops where a legume and a cereal are grown together synergistically.

At their inception all agricultural systems included a legume: beans in the Americas, cowpea in Africa, soybean in Asia and pea, lentil, faba bean and chickpea in the Mediterranean / and Middle-Eastern area area. This is for two reasons: first the protein provided by legumes complements that of grasses in its amino acid composition so together they provide a balanced diet for people and their livestock. Secondly legumes contribute to soil fertility largely through the inclusion of fixed nitrogen: recycling nitrogen through manure alone is not sufficient to maintain long term fertility. This balanced system was maintained for millennia, but changed because of the availability of nitrogen fertilizer, and has been partitioned so that distinct areas specialise in producing different crops.

The EU context
In Europe approximately 70% of plant derived protein is imported, and in arable farming legumes contribute about a quarter of the area that would be expected as compared to other agricultural systems. This means that European agriculture is exceptionally dependent on nitrogen fertilizers. In addition, the imported nitrogen (as protein) is not efficiently recycled throughout the area under cultivation. Europe therefore has several problems: nitrogen water pollution together with agriculture that has an excessive energy demand and greenhouse gas footprint. The greenhouse gases are methane largely from ruminants, carbon dioxide from the energy demand of fertilizer production as well as on-farm and transport, and nitrous oxide largely from the use of nitrogen fertilizers.

Environmental footprint
Carbon dioxide is the best known greenhouse gas and in Europe the net agricultural contribution to total CO_2 emission is about 2%. This may seem small, but plant growth is responsible for CO_2 fixation, so agriculture could be a net CO_2 sink. Methane is at least 20 fold more damaging than CO_2 as a greenhouse gas, and ruminants are a major source, but this CH_4 production is a property of gut function that responds to diet, and notably condensed tannins in pasture legumes can reduce CH_4 production by grazing animals. Nitrous oxide is more than 300 times as effective as CO_2 as a greenhouse gas, and the IPCC estimates that direct N_2O emission should be considered as 1% of applied nitrogen (though higher values ranging from 3 to 5% have been estimated recently by the Chemistry Nobel laureate Paul Crutzen). Furthermore, nitrogen application results in indirect N_2O emissions and considerable amounts of N_2O are emitted during the fertiliser manufacturing process. Nitrous oxide represents thus a major greenhouse gas contribution from agriculture (agricultural N_2O represents 75% of total N_2O emissions), and this contribution comes directly from nitrogen fertiliser application. Legume crops, such as soybean, have been recently reported to generate 3 to 4 times less of this gas than a cereal receiving nitrogen fertiliser, so increasing the use of legumes in agriculture has the potential to minimise greenhouse gas production and the environmental footprint of agriculture.

Product quality
Legumes are widely grown for food both as grain (pulses) or fresh as a vegetable. They are an important protein source for people both directly as food and, to a higher volume, indirectly as animal feed. For both they have a high and widely recognised quality. For animal feed, grains are used with minimal processing and for this reason the quality demand of seed for feed is high and therefore it is important to optimise both nutritional potential and nutritional availability, while also maximising yield potential. For forage and pasture, legumes provide protein and nutritionally important compounds. Legume shrubs are used to reclaim land from desertification, where their ability to fix atmospheric nitrogen compensates for poor soil fertility, the organic contribution of these plants to soil improves its fertility. Legume trees are prized for their wood quality, and in mixed stands they can improve the quality of companion species.

Research demands
It is clear that legumes could be an important component of a strategy for minimising the environmental impact of agriculture, especially in its contribution to climate change. The observations made above suggest that increasing the role of legumes in European agriculture will minimise its adverse environmental impact. However this needs careful quantification and full life cycle analysis to be sure that unforeseen consequences do not obviate what appears to be a benefit. *A systematic study of the N_2O emission from a range of crop systems and rotation would be a high priority*. *Similarly the impact of legume-derived green manure should be considered as an alternative to urea or inorganic nitrogen fertiliserin the perspective of an important extension of organic agriculture.*

If economic drivers respond to environmental cost we can anticipate a demand for increasing the inclusion of legumes in agriculture. This will require continuing efforts to maintain yield and quality as well as adapting crops, for example with maturity date to better fit agronomic practice. We can anticipate that the time between successive occupation of the same field by a legume crop will diminish. Soil borne disease is a major constraint to achieving this, and the root pathogen *Aphanomyces* has already depressed the area under legume cultivation in the EU. Access to genetic resistance will require the combination of components of resistance depending on the use of molecular markers. The possibility of disease control through the manipulation of the microbial ecology associated with legume roots also deserves further characterisation. *An integrated study of legume root biology focussed on the control of root diseases would be timely*. Similarly the impact of pests and diseases is likely to increase as the population density of host plants increases. This requires a pre-emptive study to incorporate resistance or tolerance in the germplasm of major European legume crops. A complementary strategy could be to deploy a range of legume species which could require some improvement in cold tolerance. *Temperature dependence and water relations of legume crops are key determinants of their utility and so their optimisation should be a target.*

Anticipating an increase in the use of legumes in agricultural systems highlights the need for optimising the productivity of legumes, and ensuring that the quality of the crop is optimised for distinct end uses. *Furthermore this creates the opportunity to design novel cropping systems that maximise the contribution of legumes to the system as a whole, which should embrace forage, pasture and arable crops.*

The main public good associated with legume crops is a consequence of biological nitrogen fixation. It follows therefore that the efficiency of this system needs study. A great deal has been learnt recently on the basic plant genetics of the very early steps of this process, but *the genetics of the efficiency of nitrogen fixation in agriculture needs attention, both in terms of the efficiency of nitrogen use by the legume and the recycling of non-harvested nitrogen to the subsequent crop.* It is important to determine the presence of efficient rhizobial strains specific of the diverse cultivated legumes (pulses, forages and trees) in the variety of European soils and develop proper rhizobial inoculants when required.

The generation of biofuel is currently much debated, but there is a consensus that a long term solution will require new approaches to the conversion of total biomass to energy, and probably this will not depend on annual crops. Alfalfa is a low input perennial legume which has a high biomass yield and could produce two major by-products for biorefineries, proteins (from leaves) for food and feed, and cellulose (from stems) for bioethanol. The close relatedness of alfalfa (*Medicago sativa*) to the model legume *Medicago truncatula* should facilitate its genetics. Another area under active consideration is short rotation coppice. Although this mainly harvests cellulose, it has a nitrogen demand. It would therefore appear worthwhile to consider the potential role of legume tree species, alone or in combination with others to contribute to sustainable coppice and forestry. Unfortunately there is no native legume tree in European forests, but *Robinia pseudoacacia* has been widely cultivated for several centuries. This fast growing species originated in the Appalachian mountains in America but also fixes efficiently nitrogen in European soils. The wood is of high quality and can be used for a variety of functions when grown in forestry and can supply biomass when coppiced. This species has received little attention genetically, but is closely related to the two model legumes for which extensive genomic and genetic resources are available. The plant has a small genome, can be selfed or crossed and has a short minimum generation time. *The development of genetic resources for this species would facilitate its positive contribution to sustainable forestry and biomass production.*

The number of legume crop species is large, ranging from fenugreek (*Trigonella foenum-graeum*) to soybean (*Glycine max*), and these many diverse species are adapted to a range of climate types, basically with summer or winter rain. Consequently the species of interest differ between ecogeographical zones. This has the tendency to fragment effort, but we know that information can be translated between species relatively easily, notably between crop and model species. This means that efforts on crops of specific interest to Europe and equivalent climatic zone can be translated to others and so together contribute to our understanding of this large and diverse family of plants. *Comparative genetics and genomics of legumes has the potential to enhance crop improvement*.

The impact of genomics on crop improvement

A major shift in legume biology has taken place because of the increased availability of genetic and genomic resources, coupled with a better understanding of the relationship between different species, notably thanks to the efforts of the Grain Legumes IP. This means that genetic and genomic studies can be focussed on amenable systems and the connection between trait responses in target and model systems needs to be explicit. *The parallel development of experimental systems in crop and model species* therefore provides an opportunity to better understand the biology of constraints to productivity and so to enable the creation or identification of appropriate genetic resources for breeding. This understanding will also come from advanced physiological modelling of plant growth and performance in a field context and can be augmented by studying natural variation in crop and model species using high throughput phenotype characterization in association with SNP or rapid sequencing assays. *The combination of genetic, genomic and ecophysiological analyses, and refined genetic tools, can help us understand the basis of, and to reduce, yield variability in major legume crops.*

During GLIP we have shown that with genomic tools it is both feasible and practical to identify and isolate genes that underlie major traits in legume crop species. The challenge for the future is to deploy these tools for the isolation of genes that underlie variability for agronomic traits that determine crop performance in the field. These will represent plant and crop architecture, the associated nutrient partitioning and response to biotic and abiotic stresses.

Sustainable agricultural practice embodies the use of locally adapted cropping systems, including grain and forage legumes and innovations such as intercropping. This will necessitate the development of a diversity of legume crops for different uses and habitats. *Consequently the tools of translational genomics should be applied to transfer data rapidly to less-characterized legume species.*

Genome sequence information in legumes is available for several legume crops, and not just from the model species. We will need user-friendly *informatics systems* to facilitate access to the diverse data bases and to provide tools for data analysis. This will be essential to make use of genome information for legume biology, comparative genetics and breeding. Efficient informatics systems will also be needed to extract information on evolutionary history: ranging from responses to selection, especially during domestication, to conservation of non-coding sequences and their consequences for regulatory circuits. Systematic analyses of the transcriptome, proteome and metabolome in legume crops can relate quality traits to useable genetic markers. *The systematic genetics of these traits in relation to quality and crop value is tractable and should permit the identification by systems biology of levers for optimizing quality.*

The genetic characterisation of germplasm resources creates the opportunity for the sampling or creation of suitable populations for *association genetic studies of agronomic traits.*

The enhancement and maintenance of systematic and comprehensive mutant populations in crop and model legumes can enable the *development of genetic resources for future use, based on models of climate change, to include expansion of pests and diseases*. *Both natural and induced sources of biological diversity, and the associated databases, should be organised, at least virtually, into a single European Legume Stock Centre to facilitate exchange and diffusion, in the same way that this has been achieved for Arabidopsis and maize*.