2 The Role of Legumes in Bringing Protein to the Table

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Abstract
This chapter examines the role of legumes in the provision of nitrogen and protein in the European food system. It follows the nitrogen cycle starting with a description of biological nitrogen fixation (BNF) and its role in generating reactive nitrogen that is essential to the functioning of ecosystems. From this, it describes the role of legumes in supplying protein for food and feed from this reactive nitrogen. A detailed account of sources and uses of plant protein in Europe is provided, including a consideration of the effect of diet. Grain legumes are lower yielding than cereals. Cereals, which are particularly high yielding in Europe, dominate most European cropping systems. BNF and protein formation are demanding in terms of plant energy (photosynthate) but this does not fully explain the difference in yield between cereals and legumes. The high yield of cereals has had a profound impact on European agricultural systems. Through the combination of fertilizer nitrogen, imported protein-rich crop commodities and specialization in high-yielding cereal production, Europe has achieved self-sufficiency in temperate foodstuffs, including commodities required to support high consumption of meat and dairy products. Cropping in the European Union (EU) is dominated by cereals and 57% of the cereals grown are fed to animals in the EU. The growth in the demand for plant protein by the expanding livestock sector has resulted in a 71% deficit in high-protein crop commodities, 87% of which is filled by imported soybean or soybean meal. Through the close relationship between this deficit and the production of livestock, European dietary patterns have profound implications for the global nitrogen cycle. A reduction in the production of livestock products from the current high level in Europe, in line with a reduction in consumption towards official health recommendations, has been estimated to reduce nitrogen pollution emissions from farming by about 40% and the demand for imported soy by 75%. If reducing the protein deficit is a priority, an integrated approach combining agricultural, environmental, food and trade policies is required.

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Introduction

Proteins are large organic molecules that are essential to life. Proteins catalyse a wide range of biological reactions and are the main component of muscle tissue. Protein is also essential for photosynthesis, so leafy plant material is protein-rich. Storage proteins located in seeds, tubers and other plant storage organs that support plant reproduction are the source of traded protein in our feed and food. The building blocks of proteins, amino acids, are nitrogen-based compounds (containing about 16% nitrogen). Proteins account for most of the nitrogen in living organisms. This nitrogen is provided to higher plants in a reactive or 'fixed' form such as ammonium or nitrate derived through fixation from inert nitrogen (N_2) in the atmosphere. Rhizobia, which are bacteria hosted as symbionts on legume roots, fix atmospheric nitrogen. Legumes are the major source of reactive nitrogen in natural ecosystems. Due to the ready supply of nitrogen, legumes are also rich in protein. Legumes therefore play a critical role in the nitrogen cycle and in the supply of protein, both in natural ecosystems and in farming systems, especially where the use of fertilizer nitrogen is restricted. The purpose of this chapter is to describe the link between these fundamental nitrogen-related ecological processes and the functioning of our food system, and to derive conclusions for the development of legume-supported cropping systems.

Legumes: the Mainstay of Protein Provision in Natural Terrestrial Ecosystems

Dinitrogen (N_2) in air is inert, and splitting and reducing it to generate reactive nitrogen available for biological processes requires substantial inputs of energy in the three major pathways: (i) atmospheric fixation taking place in lightning; (ii) biological fixation; and (iii) industrial or synthetic fixation. In synthetic nitrogen fixation, hydrogen, usually derived from methane (CH_4) in natural gas, is combined with nitrogen at high temperature and pressure in the Haber–Bosch process. For fertilizer production, ammonia is usually converted to urea or ammonium nitrate and the total energy required is about 49 MJ/kg fertilizer nitrogen (Fehrenbach *et al.*, 2007), or the equivalent of about 1 kg of natural gas.

Biological nitrogen fixation (BNF) depends on only a few types of microorganisms: (i) rhizobia bacteria (of the family Rhizobiaceae) on legumes; (ii) actinomycetes (*Frankia* spp.) on about 200 woody species belonging to eight angiosperm families such as *Alnus* spp.; (iii) free-living soil bacteria (*Azotobacter*, *Azomonas*, *Clostridium*, *Citrobacter* and others); and (iv) cyanobacteria that are either symbiotic (*Anabaena* spp. with the aquatic fern *Azolla* spp.) or free-living. In this BNF, atmospheric N_2 is reduced to ammonia (NH_4^+) through the bacterial nitrogenase enzyme system. In mixed plant communities, the fixed nitrogen in legumes becomes available to the other plants through root exudates, by degradation of senescent organs, or via the excretions of animals grazing on the legume.

Supported by BNF, legumes are very effective pioneering plants. Legume species of the genus *Genista* (brooms) are so closely associated with colonizing new soils that the common and Latin names of one, *Genista aetnensis* (Mount Etna broom), refer to the mountain where it is a prominent feature of vegetation on old lava flows (Fig. 2.1). Legumes remain common in natural plant communities beyond the pioneering stage, and most of the nitrogen in natural and semi-natural ecosystems, including that in animal protein, is ultimately derived from legumes.

Fig. 2.1. The pioneer character of legumes is clearly exhibited by Mount Etna broom (*Genista aetnensis*), so named because of its prevalence on old lava flows on the lower slopes of Mount Etna. (Photo credit: Velela on Wikimedia.)

The partnership between legumes and rhizobia

BNF in legumes depends on effective symbiosis between the host legume plant and the rhizobium. Rhizobia are relatively specific to their host legumes. Lucerne (alfalfa; *Medicago* spp.) and sweet clovers (*Melilotus* spp.) are associated with *Sinorhizobium meliloti*; clovers (*Trifolium* spp.) with *Rhizobium leguminosarum* biovar. *trifolii*; pea (*Pisum* spp.), vetches (*Vicia* spp.) including faba bean (*Vicia faba*) and lentil (*Lens culinaris*) with *R. leguminosarum* bv. *viciae*, common bean (*Phaseolus vulgaris*) with *R. leguminosarum* bv. *phaseoli*; soybean (*Glycine max*) with *Bradyrhizobium japonicum*, lupin (*Lupinus* spp.) with *Bradyrhizobium* 'sp.'; and bird's foot trefoil (*Lotus* spp.) with *Mesorhizobium loti* (Amarger, 2001).

The compatible rhizobia enter the plant via plant-derived infection threads and occupy root cells to form the nitrogen-fixing nodule. The nitrogen-fixing enzyme nitrogenase is produced within the bacterium, and red leghaemoglobin (a molecule similar to the haemoglobin) in the cytoplasm of the root nodule cell controls the flow of oxygen to the bacteria. As a result, active nodules have characteristic pink centres. Nitrogenase is active as long as the plant is metabolizing, even close to 0°C (Lindström, 1984; Stoddard *et al.*, 2009).

Enhancing fixation

The use of inoculation with the 'right' rhizobium for a given legume is an important production technology in some situations. For pea, faba bean and clover, rhizobia native to European agricultural soils are generally regarded as sufficient to establish symbiosis, but inoculation of seed with improved selections can increase BNF, particularly where a crop is new to a site, or where the soil pH is low (van Kessel and Hartley, 2000; Lindström *et al.*, 2010). Inoculation of lucerne where it has not been cropped for a long period is often beneficial. Even where the same inoculant species infects several hosts, there are differences between bacterial strains, so the isolate of *R. leguminosarum* used on pea differs from that used on faba bean or clover. Selections (biovars) of *R. leguminosarum* have been identified that optimize the amount of nitrogen fixed by each host species (Lindström, 1984; Stoddard *et al.*, 2009). Inoculation with *Bradyrhizobium japonicum* is considered essential for optimal nitrogen fixation in soy (see Chapter 7, this volume).

There are several methods of inoculating legumes, and inoculants often require special care to maintain their viability. Furthermore, rhizobial inoculants and grain legumes must match to realize the BNF benefits. Other non-rhizobial bacteria such as plant growth-promoting bacteria can also improve nodulation and grain yield with co-inoculation with crop-specific rhizobia (Tariq *et al.*, 2014). However, inoculation of seed is not always useful. When the population of indigenous root-nodule bacteria for the given crop is high, they can out-compete the introduced inoculant bacteria (Thies *et al.*, 1991). The survival of the indigenous population of *R. leguminosarum* is affected by soil pH (Leinonen, 1996), so soil pH is a good indicator of the potential survival of rhizobia.

Costs of biological nitrogen fixation

Analogous to synthetic nitrogen fixation, BNF requires energy. Each molecule of atmospheric nitrogen (N_2) fixed by conversion to two ions of NH_4^+ (ammonium), requires 16 molecules of ATP (the molecule that transfers energy within cells), representing a cost of 10–15 g glucose per gram of nitrogen fixed (Hay and Porter, 2006). This energy cost is met by the legume plant in the form of photosynthate supplied to the rhizobia and this has consequences for the yield of legumes compared with cereals and other non-leguminous plants fertilized using synthetic nitrogen fertilizer or manures.

However, there are compensating effects. The availability of biologically fixed nitrogen obviates the need to reduce nitrate to ammonium, which avoids a cost of 4–5 g glucose per gram of nitrogen (Hay and Porter, 2006), a saving estimated to be equivalent to 10 g glucose per gram of nitrogen in faba bean (Schilling *et al*., 2006). This partly compensates for the energy cost of the BNF. Vertregt and Penning de Vries (1987) reported that BNF has a net cost of 4.5 g glucose per gram of nitrogen fixed. The overall effect on crop yield potential depends on whether the growth of the plant is limited by its ability to photosynthesize ('source limited') or by its ability to use the photosynthate for new plant tissue ('sink limited'). In faba bean and soybean, rhizobial symbiosis uses 4–16% of the host plant photosynthate, but this can be compensated by an increased photosynthetic rate (source) as the plant responds to the demand (sink). The increased demand stimulates photosynthesis so the net yield penalty of BNF is zero (Kaschuk *et al*., 2009). In pea, yield was found to be source limited, and a significant yield penalty attributable to BNF was shown (Schulze *et al*., 1994). Crops subjected to stresses are source limited, and in these cases there is a negative effect of BNF on yield, on top of that caused by the stress itself. A review concluded that legumes produce about 15% less above-ground biomass per unit of photosynthetically active radiation intercepted than carbohydrate-rich crops (Gosse *et al*., 1986) but much of this can be accounted for by the higher energy requirements of protein synthesis. The synthesis of protein requires about 60% more glucose than the synthesis of starch (Penning de Vries *et al*., 1974) even though the energy content of starch and protein is the same. This, and the energy cost of BNF, only partly explains why grain legumes are lower yielding than cereal crops (Table 2.1).

Quantity and Fate of Fixed Nitrogen

Estimating the quantity of nitrogen fixed by legumes is of interest to agriculturalists, environmental scientists and policy makers. Pea and faba bean were estimated to derive 60% and 74% of the nitrogen in their shoot biomass from BNF (Peoples *et al*., 2009). However, estimating total BNF requires estimates of nitrogen in roots and released to the soil by roots. Calculations based on root:shoot ratios and root nitrogen content suggest that below-ground nitrogen is only 8–14% of above-ground nitrogen in pea, faba bean and narrow-leafed lupin (Baddeley *et al*., 2013). Others have estimated that 30–60% of total plant nitrogen may be below ground (Peoples *et al*., 2009), representing up to 100 kg N/ha for faba bean

(Jensen *et al.*, 2010). Some of the differences may be due to nitrogen deposited in the root zone from root exudates, shed cells and dead root fragments. Such nitrogen represented 12–16% of plant nitrogen, or 80% of below-ground nitrogen, from pea, faba bean and white lupin (Mayer *et al.*, 2003).

Table 2.2 presents data assembled by Baddeley *et al.* (2013) on a range of nitrogen-related parameters for seven grain legume species. This shows that nitrogen harvest indices are generally below 0.80, which is lower than in cereals (e.g. as reported by HGCA, 2006; Barraclough *et al.*, 2014). Therefore the high

Table 2.1. The average annual grain yield (t/ha), yield of protein, starch and oil in grain (t/ha) and the concentration of protein, starch and oil in grain for four major grain legumes and wheat and oilseed rape as two non-legume reference crops in Europe. (Crop production data from FAOSTAT, 2015; composition information from Feedipedia, 2015.)

	Yield (t/ha)				Concentration in grain (%)		
	Grain	Protein	Starch	Oil	Protein	Starch	Oil
Faba bean	2.8	0.81	1.25	0.04	29	44.7	1.4
Pea	2.7	0.68	1.39	0.03	25	51.3	1.2
White lupin	1.6	0.61	0.00	0.16	38	0.0	10.0
Soybean	2.6	1.07	0.17	0.55	41	6.4	21.3
Wheat	5.6	0.67	3.87	0.10	12	69.1	1.7
Oilseed rape	3.1	0.63	0.11	1.43	21	3.4	46.1

Table 2.2. Constants and calculated values used to derive estimates of fixed nitrogen (N) and N balance for FAO[a] classes of grain legumes. All calculated quantities are relative to 1 t of grain produced. (Coefficients from Baddeley *et al.*, 2013.)

Data on crop parameters relating to 1 t of grain	Faba bean	Chickpea	Lentil	Yellow lupin	Pea	Soybean	Vetches
Grain protein concentration (%)	29	22	29	36	25	40	29
Dry matter harvest index	0.49	0.31	0.42	0.44	0.51	0.52	0.34
N harvest index	0.68	0.80	0.65	0.84	0.73	0.73	0.79
Above-ground N (g/kg)	59.5	37.3	61.0	58.5	47.2	75.0	50.5
Root:shoot ratio	0.23	0.44	0.37	0.28	0.11	0.20	0.35
Root biomass production (t)	0.40	1.22	0.77	0.551	0.19	0.33	0.89
Root N concentration (%)	2.2	1.4	1.4	1.2	2.2	1.7	2.9
Root N production (kg)	8.9	17.1	10.7	6.5	4.1	5.7	25.8
Proportional rhizodeposition	0.18	0.53	0.15	0.17	0.12	0.20	0.15
Rhizodeposition (kg)	12.6	28.8	10.8	11.1	6.2	15.7	11.4
Total N production (kg)	81.1	83.2	82.5	76.1	57.4	96.5	87.7
Proportional atmospheric N	0.77	0.50	0.70	0.82	0.70	0.52	0.72
N fixed (kg/t grain)	62	42	58	62	40	50	63

[a]FAO, Food and Agriculture Organization of the United Nations.

protein content in legume grain is attributable to a high nitrogen concentration in the plant generally rather than an especially high rate of transfer of nitrogen (protein) into the grain.

The data presented in Table 2.2 led to estimates of rates of BNF in grain legume crops from 90 kg/ha to 170 kg/ha on the basis of average yields. Greater fixation is supported by higher yielding crops.

BNF in temperate forage legumes has been examined by Peeters *et al*. (2006). Estimates range from between 100 kg N/ha and 350 kg N/ha for white clover, and between 100 kg N/ha and 400 kg N/ha for red clover and lucerne. This nitrogen fixation supports 7–11 t dry matter (DM)/ha for white clover and grass; 9–16 t DM/ha for red clover and grass (Peeters *et al*., 2006) and 10–15 t DM/ha for lucerne (Annicchiarico *et al*., 2015).

Baddeley *et al*. (2013) estimated that 811,000 t of nitrogen was fixed in the European Union (EU) (not including Croatia) by agricultural legumes (grain and forage legumes) in 2009. (This compares well with the model estimate presented later in the chapter in Fig. 2.4.) While this is a significant quantity of nitrogen, it is only approximately 5% of the reactive nitrogen entering Europe's farming systems (in fertilizer and imported feed). The total amount of nitrogen fixed by forage legumes was estimated to be 586,000 t, with approximately 70% from permanent pasture and 30% from temporary grassland. De Vries *et al*. (2011) estimated the total fixation by agricultural legumes at a slightly higher value of 1.12 million t based on four European nitrogen budget models that include about 5 kg/ha of nitrogen fixation by free-living microbes in all non-legume arable land.

Legumes and Our Protein Supplies

In nature, the ready supply of reactive nitrogen from BNF supports high concentrations of protein in legume plant tissues, especially in seeds. In grain legumes, seed protein concentrations range from 20% to 25% in common bean, lentil, chickpea and pea, to over 40% in soybean and yellow lupin. The higher protein concentrations are found in those legume species that store other energy in oil. This has implications for the economic competitiveness of starchy grain legumes such as faba bean and pea because a relatively low cereal price tends to depress the price of pea and faba bean due to the high proportion of starch in the seeds.

Carbohydrate-rich cereals dominate most European cropping systems. In these systems, oilseed rape and sunflower are the dominant alternative to cereals, referred to as 'break' crops because they break the sequence of cereal cropping. These oilseed break crops lead to higher yields in subsequent cereal crops and complement cereals with high protein and oil contents. The grain yield performance of grain legumes compared with wheat and oilseed rape is a good indicator of how well grain legumes can compete for land resources (Stoddard, 2013; de Visser *et al*., 2014). Because these are average yields for the EU, there are many regions where the data in Table 2.1 are only partly relevant. However, important generalizations can be drawn. On average, the annual yield of starch-rich grain legumes (faba bean and pea) is about half that of wheat and similar to that of oilseed rape. In order to maintain economic output, the price per tonne of grain legumes must be substantially higher than that of wheat and comparable with oilseeds taking into account additional rotational benefits from legumes. Such a position depends on a high price for protein compared with oil and starch.

Protein quality

The quality of the protein for feeding, as determined by the amino acid composition, also plays a role in the competitiveness of legumes. Because of its amino acid profile (Table 2.3), soy is particularly highly valued for inclusion in many animal feeds and valued also because of the high digestibility of the essential amino acids. For large-scale feed manufacture, the availability of large batches shipped into Europe is an additional advantage. However, grain legume proteins generally complement cereal proteins in a similar way. They are all higher in lysine than cereals. The notable difference between soybean and other legumes is the generally higher concentrations of methionine, cysteine and tryptophan in soy protein, which combined with a high concentration of lysine provides the foundation of a well-balanced supplement in cereal-based feeds for monogastrics. There are also differences between legume species in terms of the characteristics of the fibre fraction, but all grain legume species deliver high-quality protein materials suitable for use in Europe's livestock sectors.

The recently completed GreenPig project showed clearly that pea and faba bean can be used to completely replace soy in feed for growing and fattening pigs (Houdijk *et al.*, 2013; Smith *et al.*, 2013). This good performance compared with that reported in earlier research is attributable to advances in balancing ingredients using standardized ileal digestibility (Stein *et al.*, 2005) and to the use of synthetic amino acids to optimize the amino acid profiles.

Europe's sources of plant protein

European agriculture is often characterized as being heavily reliant on imported plant protein (e.g. Häusling, 2011; USDA, 2011). For assessing the extent of the protein deficit and especially opportunities to reduce it, a wider approach examining the sourcing and use of all plant proteins is needed. To consider this, we first

Table 2.3. The concentration (%) of major limiting amino acids in the protein of four grain legume crops and two non-legume reference crops used for animal feed in Europe. (From Hazzledine, 2008.)

	Lysine	Methionine	Cysteine	Tryptophan
Faba bean	6.2	0.7	1.2	0.8
Pea	7.2	0.9	1.5	0.9
White lupin	6.2	0.7	1.2	0.9
Soybean	6.2	1.4	1.5	1.4
Wheat	2.9	1.6	2.3	1.3
Oilseed rape	5.6	2.0	2.4	1.4

examined the transfers of protein in the major traded crop commodities (Table 2.4). We estimate that the total consumption of protein derived from tradable arable crop products (import + EU production - export) was 55 million t in 2011, of which 52% is provided by cereals. Of this cereal protein, 60% is fed to animals. In addition, forage maize provided 3.9 million t, almost all for beef and milk production. There is a net export of cereals (the only major crop commodity group that has a net export) and EU cereal production in total equates to 53% of tradable protein consumption. When all supplies and trade are considered, the EU is 69% self-sufficient in tradable plant protein. Imported soy accounts for 62% of the high-protein commodities used (pulses and oilseed meals). The deficit in these high-protein commodities is 71%

Table 2.4. The European Union (EU) tradable plant protein balance – net import, EU production and use of protein in feed or food.[a]

	Net import	Production	Use in animal feed	Use in food
Crop quantities (million t)				
Soybean	36.9	1.3	38.1	0.1
Oilseed rape	2.7	19.3	22.0	0.0
Sunflower seed	4.9	8.5	13.4	0.1
Other oilseeds	3.5	0.0	3.5	0.0
Pea	0.1	1.6	0.8	0.9
Faba bean	0.2	1.9	1.2	0.9
Fruit and vegetables	14.0	192.7	8.9	198.5
Cereals	–15.6	293.1	167.7	110.9
Forage maize (DM)[b]	0.0	55.0	55.0	0.0
Protein quantities (million t)				
Soybean	15.13	0.53	15.62	0.04
Oilseed rape	0.57	4.05	4.62	0.00
Sunflower seed	0.68	1.45	2.13	0.00
Other oilseeds	0.91	0.00	0.91	0.00
Pea	0.02	0.38	0.19	0.21
Faba bean	0.06	0.46	0.30	0.22
Fruit and vegetables	0.14	1.93	0.09	1.98
Cereals	–1.80	29.06	16.38	10.88
Total ‘tradable’ crops	15.71	37.86	40.24	13.33
Forage maize	0.0	3.85	3.85	0.0
Total from arable crops	15.71	41.71	44.09	13.33

[a]The data are derived from FAOSTAT (2015), accessed in January 2015. Data on soy, rapeseed and sunflower meal were converted to seed equivalents using the following conversion factors: soy 1.25; oilseed rape 1.83; sunflower 2.27. The protein contents of the seed quantities so derived come from Feedipedia (2015) as follows: soy 41%; oilseed rape 21%; sunflower 17%; pea 25%; faba bean 29%; fruit and vegetables (including starch crops) 1%. The estimate of forage maize production comes from Rüdelsheim and Smets (2011) adjusted for the maize area in Germany used for biogas production by reducing the total area from 5.0 million ha to 4.6 million ha. The forage maize yield is assumed to be 12 t dry matter/ha with a protein content of 7% (from Feedipedia, 2015). Data for some co-products of the food sector such as dried distillers grains with solubles (DDGS), sugarbeet pulp, and food waste recycled into animal feed are not considered because of lack of data. FEFAC (2014) estimate that about 17 million t of such material are used in compound feed manufacture.
[b]DM, Dry matter.

and imported soy meets 87% of that deficit. These data confirm other assessments based on industry data that the EU deficit in high-protein materials is around 70%. Houdijk *et al*. (2013) reported a deficit of 68% for 2011 in the EU.

The total agricultural area of the EU (EU-27) was 185 million ha in 2012, of which about 67 million ha is grassland (FAOSTAT, 2015) (i.e. 36% of the agricultural area). These grasslands make a substantial contribution to the total protein production in Europe. They are mainly transformed into meat and milk produced by cattle, sheep and other ruminants for human consumption. The total protein production from EU grasslands is estimated here on the basis of two assumptions on yields (based on expert opinion): annual average production of 4 t DM/ha or 6 t DM/ha (Table 2.5). It must be emphasized that there are few relevant data available on the productivity of European grasslands and the assumptions made in Table 2.5 are based on our expert opinion. There are great uncertainties about the efficiency of grazing. This estimates that the total protein harvested (including grazing) from grassland is between about 40 million t and 60 million t, which compares with 42 million t from arable and permanent crops (Table 2.4).

Combining these data, the total plant protein consumption in the EU ranges from approximately 100 million t to 120 million t. A net import of 16 million t accounts for 13–16% of total protein supplies where protein from grassland is included.

Table 2.5. Protein production from European permanent and temporary grasslands on the basis of two yield assumptions.[a]

	Average/total	Grazed grass	Grass silage	Hay
Utilization assumption (grazed, silage, hay %)	100	66.7	16.7	16.7
Crude protein content (%) (Erwing, 1997)	–	16.0	13.0	10.4
Grassland area (EU-27) (Eurostat, 2013) (million ha)	67.6	45.1	11.3	11.3
Production assumption 1 (4 t/ha, DM basis)[b]	4.0	4.0	5.0	3.0
Crude protein yield (t/ha)	0.59	0.64	0.65	0.32
Total protein production (million t)	39.9	28.9	7.3	3.5
Production assumption 2 (6 t/ha, DM basis)	6.0	6.0	7.0	5.0
Crude protein production (t/ha)	0.88	0.96	0.91	0.52
Total crude protein production (million t)	59.5	43.2	10.2	5.9

[a]The authors emphasize the uncertainty in the assumptions made in this table. The assumed yields are an average for all grassland in the EU, which includes unproductive semi-natural grassland on the British Isles, short-season grassland in Scandinavia, and grassland subject to heat and drought stress in the Mediterranean region. While the assumption of 4 t/ha DM might appear low, it is supported by estimates cited by FEFAC (2014).
[b]DM, Dry matter.

The use of soy in European livestock production

There are no official data on the use of soy in the various livestock sectors but estimates have been made. Gelder *et al*. (2008) estimated the allocation of the soy to species based on feed formulation and farm practice in the Netherlands with inclusion rates in concentrate feed of 37%, 29%, 22% in feeds for broilers, pigs and laying hens, respectively. The inclusion of soy in beef and dairy concentrate feeds is lower at 14% and 10%, respectively. These estimates indicate that monogastrics (pigs and poultry) account for at least 80% of soybean meal use in the Netherlands. This results in the following rates of use on a per unit food commodity output basis: beef, 232 g/kg; milk, 21 g/kg; pork, 648 g/kg; poultry meat, 967 g/kg; eggs, 32 g/egg.

Because of the lack of official species-specific data, there is great uncertainty in these estimates. The total industrial feed production in Europe was 155 million t in 2013 (FEFAC, 2014). Our assessment of the FEFAC (European Feed Manufacturers' Federation) data suggests that inclusion rates of soy in feed is lower across the EU than suggested by Gelder *et al*. (2008) for the Netherlands, particularly for the monogastrics. This is reflected in the estimates provided by Westhoek *et al*. (2011).

Research in regions affected by nutrient surpluses caused by concentrated livestock production show that there is substantial scope to reduce the soybean meal and the total protein content of compound feeds without affecting animal performance. From farm practice, Lindermayer (2015) reported that soybean meal inclusion rates for pig fattening can be reduced to 10% with substantial reduction in nitrogen excretion while maintaining animal productivity. There is even greater scope for reducing soybean meal use in ruminants that not only digest cellulose-based feeds such as grass which provides protein, but also synthesize amino acids from non-protein nitrogen compounds in their digestive system. This means that for protein supplementation, alternatives to soybean meal are more easily adopted in milk, beef and sheep production.

Europe's Evolving Agri-food System

To understand the related roles of nitrogen and legumes in the European food system, it is useful to examine changes in food consumption and production that have occurred in recent decades. A number of forces have come together since 1960: (i) changes in trade policy; (ii) technical change in livestock production; and (iii) economic growth leading to increased disposable income. Between 1961 and 2011, livestock production in Europe increased in line with consumption from the equivalent of 822 kcal/capita/day to 993 kcal/capita/day with 395% and 170% increases in poultry and pig meat, respectively (FAOSTAT, 2015). This was facilitated by intensification in production, particularly for pigs and poultry, associated with a decoupling of livestock production from the land resource base. The FAOSTAT reports that between 1961 and 2008, the number of pigs and chickens increased significantly in the EU (63% and 56%, respectively) but there was an 11% reduction in the number of cattle and sheep. The increases in livestock numbers were less than the increase in output due to increases in productivity per animal. Changes in trade policy gave European farmers access to low-cost soy, which in effect reduced the value of home-grown sources of protein in Europe – including protein from grassland. Changes in soy imports align with changes in livestock production, particularly pigs and poultry (Fig. 2.2). Access to compound feeds and some technical developments in animal housing allowed a regional concentration of livestock production (Fig. 2.3), particularly pigs and poultry with very significant nitrogen and phosphorus pollution challenges and reduced opportunities for legume production in these regions. This scale of livestock production, based largely on European-grown cereals, is facilitated by the complementary qualities of soybean meal. Approximately 60% of Europe's cereal harvest is now used to feed livestock.

Changes in cropping

The proportion of the EU arable area under cereals has remained remarkably stable at about 57% of the annually cropped area. Between 1961 and 2011, the maize area more than doubled, and the area of oilseed rape and sunflower increased from 1.3 million ha to 11.2 million ha (13% of arable cropping). Grain legume areas declined from 5.8 million ha in 1961 (4.7% of the arable area) to 1.9 million ha in 2011 (1.8% of the arable area).

While FAOSTAT data indicate that the proportion of EU agricultural land under grass has remained stable overall, Eurostat data show that between 1970

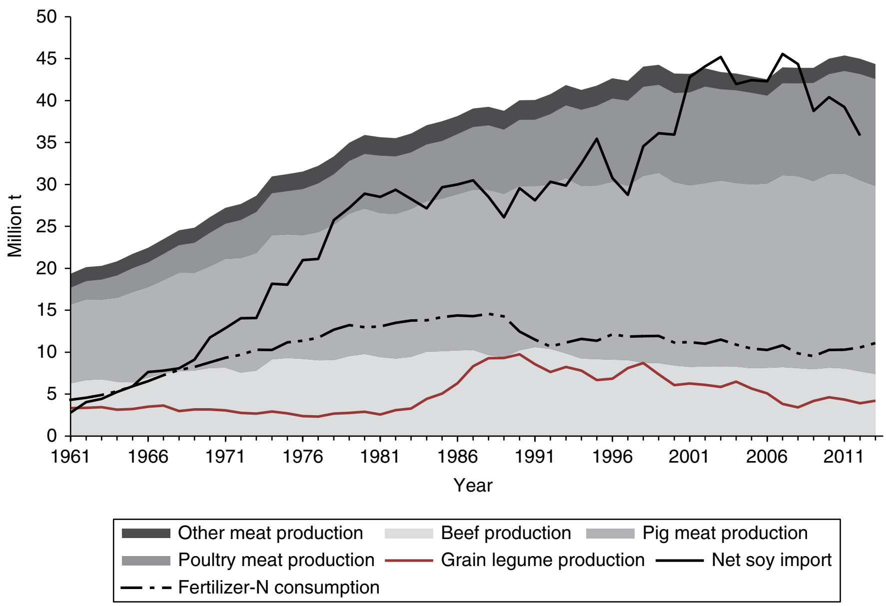
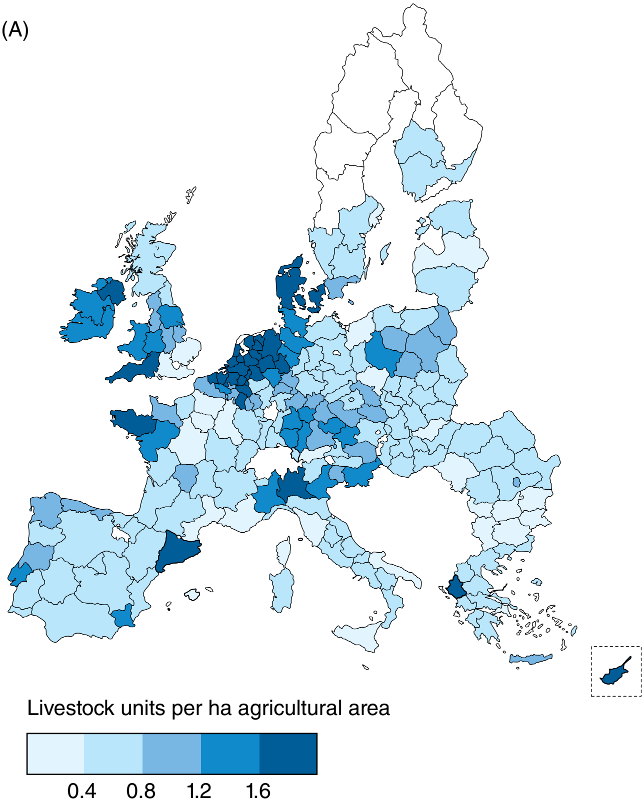


Fig. 2.2. Changes in the production of meat and corresponding changes in fertilizer nitrogen use, protein crop production and net soy import for the EU-27 (1961–2011). (From calculations based on data from FAOSTAT, 2015.)

(A)



(B)

Fig. 2.3. Increased and concentrated livestock production, particularly pigs and poultry, has had consequences for the demand for concentrate feeds (including soy) and the nitrogen cycle. (A) Variation in regional livestock densities across Europe. (B) Intensive pig production in north-west Germany combined with specialization in carbohydrate-rich cereals crops (in this case rye).

and 2012, about 9.6 million ha of permanent grasslands (about 36% of 1970 levels) were lost in the founding six member states of the EU (Eurostat, 2013).

The annual increase in cereal productivity of about 0.15 t/ha (Supit, 1997), facilitated by the switch to autumn sowing, fertilizers and plant protection products, has probably been an important factor in promoting conversion of grassland to arable cropping. The rate of increase in yield of cereals was higher than that of grain legumes in most regions (Stoddard, 2013), reinforcing the dominant position of cereals. Intensification, driven by the comparative advantage of specialization, has resulted in more concentrated production and more homogeneous farming systems.

Trade policy also had a large effect. The 'Dillon Round' of the General Agreement on Tariff and Trade (GATT) negotiations in 1962–1963 resulted in European agreement to tariff-free imports of protein-rich feedstuff for animal feeding. These imports in effect reduced the value of European plant protein sources, compared with starch-rich crops that benefited from some market support. This situation was reinforced in 1992 in the Memorandum of Understanding on Oilseeds (often referred to as the 'Blair House Agreement') negotiated during the GATT Uruguay Round. Europe is now the second largest importer of soy (China is the largest). Imported soy accounted for about 19 million ha of land outside the EU in 2008 and is the largest cause of the EU net 'virtual' land import (39% of total virtual land imports). It corresponds to the size of the German agricultural area (von Witzke and Noleppa, 2010). This trade in soy has implications for the global carbon and nitrogen cycles and has supported land-use change, directly and indirectly leading to habitat losses and greenhouse gas (GHG) emissions in South America (Malingreau and Tucker, 1988; Fearnside, 2001, 2007; Carvalho and Batello, 2009; Murphy-Bokern, 2010).

Diet, legumes and the nitrogen cycle

Given the connection between livestock production and soy use (Fig. 2.2), what is the effect of food system change on the nitrogen cycle, and what role do legumes have in such change? Using the data from biophysical modelling reported by Westhoek *et al.* (2014) we can estimate the flows and conversions of nitrogen in the European food system (Fig. 2.4). This shows that the European agri-food system uses 17.7 million t of reactive nitrogen, 64% of which is provided in fertilizer form. About 18% is provided by BNF, dominated by BNF in soybean grown outside Europe. This 17.7 million t of nitrogen supports a flux of 87 million t of plant protein used directly or indirectly for food.

These model estimates are in reasonable agreement with our estimates based on FAOSTAT commodity data (Table 2.4). However the Westhoek *et al.* (2014) estimate for protein from grassland is significantly lower than the estimates presented in Table 2.5. In reasonable agreement with the results in Table 2.4, the EU is more than 80% self-sufficient in plant protein. According to this modelling work, about 35% of all the plant protein used is from grassland (from 36% of the utilized agricultural area). About 86% of the plant protein used is consumed by livestock.

Only about 13% of the reactive nitrogen entering the system ends up in human food. Much of the loss occurs in the conversion of plant protein to

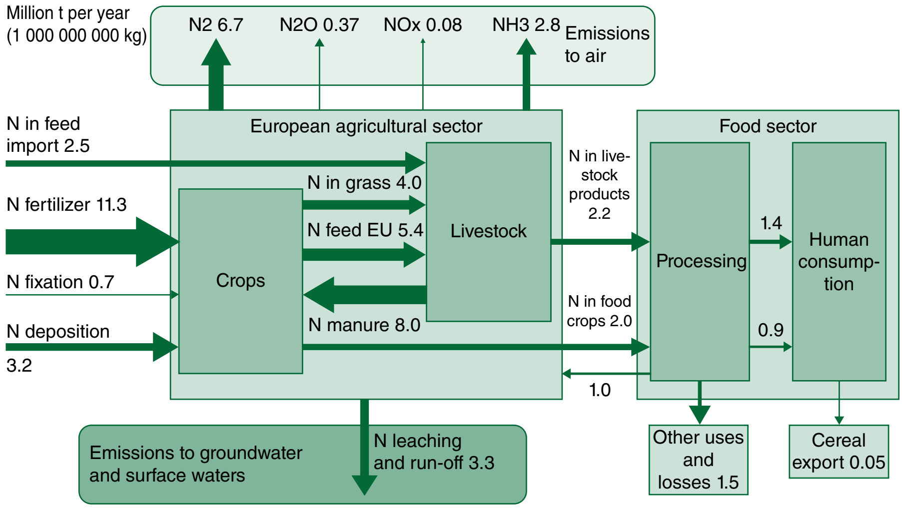


Fig. 2.4. Nitrogen (N) flows (million t/year) in the European Union (EU) agricultural and food system based on data for the EU-27 from 2004. (From Westhoek *et al*., 2014.)

animal protein in livestock. This raises the question of the effect of dietary change on the nitrogen cycle. Westhoek *et al.* (2014) showed that a 50% reduction in the consumption and production of livestock products (which would be in line with current public health guidelines) would result in a 40% reduction in nitrogen emissions, 25–40% reduction in agricultural GHG emissions and 23% reduction in the per capita agricultural land requirement. The EU would become a larger net exporter of cereals and the use of soybean meal would be reduced by 75%. The nitrogen use efficiency (NUE) of the food system would increase from the current 18% to between 41% and 47%, depending on choices made regarding land use.

Pointers to Change in Developing the European Agri-food System

European agriculture can be characterized as reliant on a combination of reactive nitrogen in fertilizers and in imported feeds. Supported by this external input of reactive nitrogen, arable land is allocated to high-yielding cereals and oilseeds that provide the dietary energy needed. Through the combination of fertilizer nitrogen and imported protein-rich commodities, Europe has achieved remarkably high levels of self-sufficiency in temperate foodstuffs, including that required for a high level of consumption of meat and milk. This allocation of resources, with its profound implications for the nitrogen cycle, characterizes Europe's core farming activities.

Achieving higher protein independence and decreasing the negative environmental consequences of soybean imports are desirable objectives (Westhoek *et al.*, 2011; Peeters, 2012, 2013). While the European self-sufficiency in most foods is sometimes celebrated in the policy community, the public debate about soy imports and the pollution emissions from the nitrogen cycle requires a science-based response: what are the options for change? Here we can draw conclusions directly from the analysis presented.

In line with the approach argued by Martin (2014), our calculations show that the EU has a greater protein resource than is often acknowledged. Changes in consumption, European protein production, and in the efficiency of use of protein in livestock feeding could together make a significant contribution to reducing the protein deficit. The very large effect of livestock product consumption and production on the nitrogen cycle, land use and the demand for protein-rich crop commodities means that the effect on the deficit of increased grain legume production is small compared with the effect of consumption change.

Most Europeans consume more meat and milk than is recommended for their health. Westhoek *et al.* (2014) showed clearly the consequences of this for land use, the nitrogen cycle and our soy imports. A shift towards more sustainable diets which are also healthier would have profound consequences, increase interest in grain legumes for human consumption, release land for new uses including grain legume production, and lead to a very significant reduction in the demand for soy. However, even with significant consumption change there would remain a demand for high-quality plant protein that only legumes can meet. The basic crop physiological processes that affect the yield potential in legumes only partly explain the large differences between grain legume and cereal yields in Europe. In terms of capturing solar radiation, taking into account additional photosynthetic requirements of BNF and protein production, grain legumes are physiologically less productive than cereals in Europe. This indicates that there are opportunities to increase grain legume yields. A rate of increase in grain legume yields that is faster than that of competing cereals and especially oilseeds would provide the foundation for a recovery in grain legume production in the long term.

Our analysis highlights the potential role of legumes in grassland. Even though the proportion of clover in grassland is now low, the BNF in grasslands is significant and estimated to exceed that of arable land (Baddeley *et al.*, 2013). In Chapter 9, this volume, Humphreys *et al.* highlight that increased use of white clover can be economically effective in grassland farming systems. There is considerable uncertainty in estimates of plant protein production on grassland that we provide, but we can confidently say that total plant protein production on Europe's grassland is at least similar to that on arable land, which raises the possibility of using legume-supported forage systems more intensively as a protein source. We can also infer that there is a large potential for the development of forage legumes in permanent and temporary grasslands, especially in the context of increasing prices of synthetic nitrogen fertilizer. Where converted to meat and milk, there are additional food quality benefits of forage legumes. Plant secondary compounds (PSC) in forage legumes interact with rumen microbes, resulting in higher proportions of linoleic and alpha-linolenic acid in the lipids in milk and meat (Githiori *et al.*, 2006; Jayanegara *et al.*, 2011; Willems *et al.*, 2014). Compared with grain-fed meat or milk, grass-fed meat or milk is: (i) higher in total omega-3 (and has a healthier ratio of omega-6 to omega-3 fatty acids); (ii) higher in conjugated linolenic acid (CLA) (*cis*-9 *trans*-11) (Dhiman *et al.*, 1999); and (iii) higher in vaccenic acid (that can be transformed into CLA) (Duckett *et al.*, 1993).

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