Chapter

3 Benefits of nitrogen for food, fibre and industrial production

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Executive summary

Nature of the issue

- Reactive nitrogen (N_r) has well-documented positive effects in agricultural and industrial production systems, human nutrition and food security. Limited N_r supply was a key constraint to European food and industrial production, which has been overcome by N_r from the Haber–Bosch process.
- Given the huge diversity in N_r uses, it becomes a major challenge to summarize an overall inventory of N_r benefits. This full list of benefits needs to be quantified if society is to develop sound approaches to optimize N_r management, balancing the benefits against the environmental threats.

Approaches

- When reviewing trends in European N_r production rates, including those from chemical and biological fixation processes, and the consumption of this N_r in human activities, agriculture is by far the largest sector driving N_r creation.
- Particular attention has been given to relationships between N application rates, productivity and quality of products from major crops and livestock types, including consideration of the mechanisms underlying variations in N response/outputs and the derived impacts on land use and land requirements.

Key findings/state of knowledge

- The economic value of N benefits to the European economy is very substantial. Almost half of the global food can be produced because of N_r from the Haber–Bosch, and cereal yields in Europe without fertilizer would only amount to half to two-thirds of those with fertilizer application at economically optimal rates.
- There is a wide variety in N responses at field level. For cereals, nitrogen productivity, also termed the agronomic efficiency, averages 41 kg grain per kg applied fertilizer N across the EU countries, with significant variation between the member states. Variation reflects differences in crop type, farm type, cropping practices, area, region, soil fertility and climate.
- Farmers have an economic incentive to apply only the economically optimal rate of fertilizer N, but there is no strong incentive to increase N use efficiency as the economic return on using fertilizer N is very robust, especially in high value crops. However, recent initiatives to reduce environmental impacts of N_r losses have led to an increase of N use efficiency in both crop and livestock production.
- Increasing fertilizer prices and climate change will create new incentives to increase N use efficiency. There are ample options to achieve this via N-conserving field practices such as catch crops, reduced soil tillage, better estimation of crop N requirements and improved timing and placement of N inputs. Also modifications to livestock diets, enhanced recycling of livestock wastes, prevention of ammonia loss from animal housing and field manure application can enhance benefits per unit applied N_r. Plant materials with improved composition of major storage compounds and novel feed additives, e.g. proteins from bio-fuel production, can also improve feed N responses per unit mass N_r used.

Recommendations

- Legislative drivers to reduce N_r use, including mineral fertilizer, must take account of the nitrogen benefits in agricultural production needed to maintain food and energy security, given the limited options to increase arable land area.
- New technological tools should be implemented to improve nitrogen-efficiency and the overall benefits of N_r use.

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3.1 Introduction

Nitrogen is an essential component of many compounds found in living cells within plants, animals and humans. All nitrogen in animals and humans originates in one way or another from plants or microbes because only they have the ability to convert mineral forms of reactive nitrogen (N_r), such as nitrate and ammonium, into organic nitrogenous compounds such as amino acids and nucleotides, which are the building blocks of proteins and nucleic acids essential for life. The availability of these basic mineral forms of N_r is a key factor determining the productivity of crops for food, feed, fibre and bio-energy and hence for all human activities (Sutton *et al.*, 2011, Chapter 1, this volume). The main paths for production of these mineral N_r forms are fertilizer manufacture, especially through the Haber–Bosch process, and biological nitrogen fixation in crops.

3.1.1 What are the benefits of reactive nitrogen?

The provision of reactive nitrogen through mineral fertilizers has contributed greatly to the increased production of agricultural products needed to feed the increasing global population (Erisman *et al.*, 2008) and hence to food security. In 1900, world agriculture was able to sustain around 1.6 billion people on 850 million ha of agricultural land using mainly extensive cultivation practices without mineral fertilizers. The same combination of agronomic practices extended to today's 1.5 billion ha cropland would feed around 3 billion people, i.e. no more than around 50% of the present population at the generally inadequate per capita level of year 1900 diets. Today, synthetic fertilizer N has been estimated to be the basis for the production of almost 50% of the food consumed by mankind (Smil, 2000; Erisman *et al.*, 2008).

In this sense, the use of reactive nitrogen provides huge benefits for man, but in order to maximize these benefits, the efficiency of use of nitrogen inputs should be optimized. It should also be noted that in this chapter, benefits are defined relatively broadly, including economic as well as social, health and political (stability) values.

For the major cereal food crop in Europe, wheat, it can be estimated that the agronomic benefit obtained by application of N fertilizer amounts to a yield increase from 86 to 150 million tons of grain per year (assumptions: 27 300 million ha of wheat in the EU-27, average yield of 5.5 t grain/ha, at 112 kg fertilizer N/ha; EFMA, 2009), based on an average yield without mineral N fertilizer in ecological farming at 60%–70% of yield with mineral N fertilizer (Offermann and Nieberg, 2000).

Fertilizer nitrogen has also played a beneficial role in avoiding natural terrestrial ecosystems from being converted to cropping systems (Tilman *et al.*, 2002). At the global scale, land use changes due to replacement of forest or natural grasslands with agricultural cropland contribute significantly (6%–17%) to greenhouse gas emissions because large amounts of carbon dioxide fixed or stored in soil organic matter are released upon cultivation. In comparison, the greenhouse gas emissions from production and use of mineral fertilizers are relatively small, constituting 0.8% and 1.3%, respectively (Figure 3.1a). The estimated contribution of European agriculture to total greenhouse gas emissions is only around 10% and land use changes in Europe have been estimated to act as a net sink for greenhouse gases (Figure 3.1b). However, this is solely driven by afforestation, with cropped land being a small net source of CO_2, although at a declining rate (Kitou *et al.*, 2009).

If less intensified agriculture becomes predominant in Europe, implying significantly lower or completely abandoning nitrogen fertilization, it may result in land use changes either within Europe or elsewhere in the world to compensate for the decrease in crop yields. Thus, von Witzke and Noleppa (2010) demonstrated that increasing production of

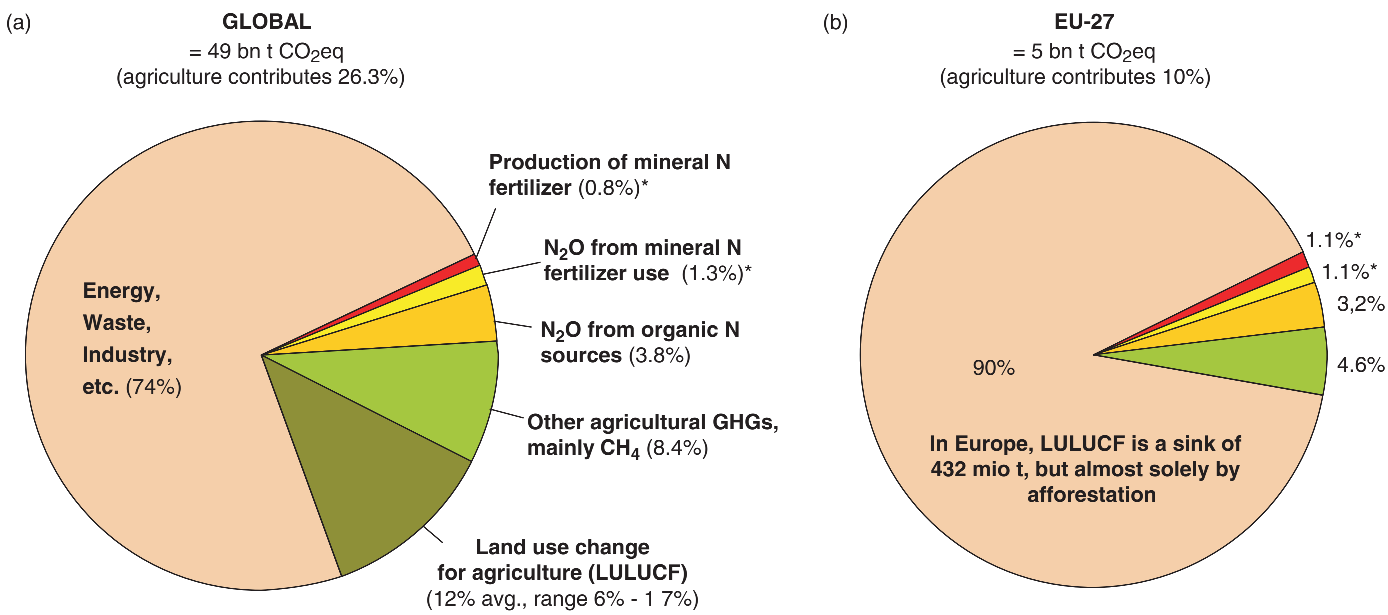

Figure 3.1 Estimated greenhouse gas emissions from production and use of mineral N fertilizers (in CO_2-equivalents) together with other agricultural activities and land use change for agriculture at (a) the global and (b) EU-27 scale (all 27 member states of the European Union as of 2007). Order of contributions in (b) the same as in (a). From Brentrup and Palliere (2008), based on IPCC (2007), Bellarby *et al.* (2008), UNFCCC (2008) and * author calculations.

agricultural commodities in the EU would significantly reduce the current EU net food imports which have increased over the past decade, and hence also the associated import of 'virtual land use' around the world. From the same point of view, agricultural intensification may be viewed as a greenhouse gas mitigation mechanism (Burney *et al.*, 2010) and a measure for preserving natural habitats (Balmford *et al.*, 2005). However, it has also been argued that extensification of European agriculture would have little bearing on the proportion of native land areas being converted into cropland. Rudel *et al.* (2009) analysed trends in crop yields and cultivated land areas for ten global regions and found that agricultural intensification was not generally accompanied by a decline or stasis in cropland area at a national scale during the period 1990–2005. They argued that many other factors influence conversion of native land to cropland, including trade and market prices, economic development and national policies and regulations. However, there is little doubt that avoiding new cultivation of major areas of native land is crucial with respect to reducing the anticipated increase in atmospheric carbon dioxide levels originating from land use change (Tilman *et al.*, 2002; Cassman *et al.*, 2003). Economically and environmentally sound nitrogen fertilization practices on the generally fertile and productive soils in the majority of European countries can contribute to this (Brentrup and Pallière, 2008) even if other factors will also play a significant role.

The pressure on native land may also be accentuated with the increased focus on replacing fossil energy with that generated on the basis of biomass. The land area required to meet the EU target for bio-ethanol in vehicle fuels by 2020 (10% blending by volume, total consumption 101 million t gasoline) would be 9.5 million ha if optimally fertilized wheat was the source, but 16.7 million ha (out of a total arable area of 98 million ha) if not fertilized with N, supposing 60%–70% yield reduction as cited above. Extensification of agricultural production in Europe in parallel with an increased European demand for bioenergy may thus increase the pressure on land resources elsewhere in the world.

Fertilizer nitrogen inputs also affect the level of soil organic matter (SOM), albeit only in a long-term perspective and often relatively moderately (Raun *et al.*, 1998). Soil organic matter is one of the most important factors for soil fertility. This is the case because soil organic matter directly affects nutrient availability via mineralization of organically bound N, P and S, via adsorption of cations and via complexation of trace elements. In addition, soil organic matter indirectly affects soil water dynamics, stability of soil aggregates, resilience against erosion and other deterioration processes. In the Broadbalk continuous winter wheat long-term experiment, which was started in 1843 on a silty clay loam in the UK, soil C in the plot annually applied 144 kg N/ha together with P and K presently amounts to 1.12% C, corresponding to about 25% more SOM than in the unfertilized control soil only containing 0.85% C (Johnston *et al.*, 2009). The fertilization with mineral N has naturally resulted in higher biomass production, higher yields and greater organic matter returns in stubble and roots than on the unfertilized plot. Application of animal manure will also enhance soil organic matter and often to a greater extent than fertilizer N alone (Johnston *et al.*, 2009).

Appropriate nitrogen inputs contribute significantly to maximizing the utilization of other costly inputs or resources for soil and crop management such as other nutrients, pesticides, labour, energy and capital as well as crop genetic potential (cultivars). An example of the interactions between genetic potential, N, P and K application can be seen in Table 3.1. Nitrogen application clearly interacted with P application, resulting in larger N use efficiency when P was also applied. The use of improved barley varieties has increased the yield, but only when N, P and K were supplied together as evidenced by the 2003–2006 data (Johnston and Poulton, 2009).

Finally, benefits of nitrogen also emerge via the very important use of nitrogen products in the manufacture of explosives, nylon and acrylic fibres, methacrylate and other plastics, foamed insulation and plastics, electronics, metal plating, gold mining, animal feed supplements, herbicides, and many pharmaceuticals (Maxwell, 2004). Other uses of reactive nitrogen compounds involve ammonia for the abatement of atmospheric NO_x and SO_2 emissions as well as a refrigerant for cooling, especially in connection with food storage. Ammonium-phosphates and -sulphates are components of metallurgy for welding and fire fighting. Despite these important applications, the

Table 3.1 Improvements in crop nitrogen use efficiency of spring barley cultivars with a gradually higher yield potential, grown in the long-term Hoosfield Barley experiment at Rothamsted, UK (Johnston and Poulton, 2009)

		Spring barley varieties (period grown) (kg grain / kg N applied)		
Treatment	**N applied (kg/ha)/yr**	**Chevalier (1852–1871)**	**Plumage Archer (1952–1961)**	**Optic (2003–2006)**
N	48	43	34	18
NK	48	46	36	24
NP	48	62	53	60
NPK	48	61	52	83

consumption of reactive nitrogen for industrial use only constitutes around one third of the total European budget, the dominating uses being crop and livestock production (see further details in Section 3.5).

3.2 Trends in European N use for crop production

3.2.1 Fertilizer N consumption and crops

The use of nitrogen fertilizers in the EU-27 countries, i.e. all 27 member states of the European Union as of 2007, increased substantially from the 1950s to the early 1980s (Figure 3.2). From the mid 1980s, the consumption of N fertilizers started to decline. A major decline occurred in the early 1990s, mainly due to the collapse of the economy of the eastern European countries (later new EU member states), but also due to the McSharry reform of the European Union Common Agricultural Policy (CAP) in 1992 (EU Glossary, 2010). This introduced mandatory set aside, causing the farming community in the old EU member states to take a proportion of the farmland out of production. Since then, nitrogen consumption in EU-27 has stabilized around 11 Tg, where it is forecasted to stay with only a small increase (3%–4%) until 2019 (EFMA, 2009). This level of consumption corresponds to an annual average quantity of around 85–90 kg N per ha of arable land. When permanent crops (fruit and vineyards) and fertilized grasslands are included, the average annual nitrogen consumption per unit surface area of total agricultural land amounts to around 65 kg N/ha.

Major nitrogen fertilizer forms used in the EU

The current use of nitrogen in western Europe (European Union countries in 2004 + Norway and Switzerland) distributed across different types of nitrogen fertilizers is shown in Figure 3.3a. Approximately 80% of the nitrogen is applied in straight N fertilizers, while 20% is applied in multi-nutrient compound fertilizers together with phosphorus and/or potassium. Urea is the most concentrated solid nitrogen fertilizer, containing 46% N on a weight basis. For this reason, urea has advantages in terms of distribution, storage and handling costs, making it the most popular N source in developing countries where it is by far the dominating fertilizer, constituting around two thirds of total fertilizer N consumption (Figure 3.3b).

In Europe, the share of urea N is much lower, only 22% (including 6% from UAN). This is partly due to the fact that the availability of nitrogen for plant uptake can be delayed since urea must first be transformed into ammonium and subsequently to the final nitrate form. This delay may particularly be a problem in the cold spring weather typical of NW parts of Europe, whereas in areas bordering the Mediterranean Sea urea consumption is traditionally higher. Another disadvantage of urea is that it implies a large risk for N loss to the atmosphere by ammonia volatilization which may exceed 20% of the applied N (Sommer *et al*., 2004). As a consequence, urea is generally much more difficult to manage properly than ammonium and nitrate-based fertilizers. The principal straight nitrogen fertilizer in Europe is calcium ammonium nitrate (CAN) which is well suited for most European soils, crops and climatic conditions, since half of the nitrogen is in the nitrate form, being immediately available to plants, and the other half is in the ammonium form. Ammonium nitrate (AN) use in Europe has declined since 2004 due to security regulations associated with its potential use as explosive. Other straight nitrogen fertilizers include ammonium sulphate, calcium nitrate and anhydrous ammonia. The latter is a highly concentrated nitrogen fertilizer (82% N) mainly used in North America. It requires specific logistics because of safety precautions necessitating special transport, handling and application equipment for injection into the soil. In Europe, it represents less than 1% of total nitrogen fertilizer used (EFMA, 2003).

Nitrogen use for major crops in the EU

Wheat and barley are the dominating cereal crops in the EU, covering nearly 40% of the area (Table 3.2). Fertilized grassland covers about 30% of the area. Oilseed rape is a large and emerging nitrogen user among intensive crops.

Compared with other crops, oilseed rape, sugar beet and wheat are the crops with the highest N application rates (Table 3.2). However, there is a considerable variation between countries as evidenced by the wide minimum–maximum range in Table 3.2. Assessed in terms of total

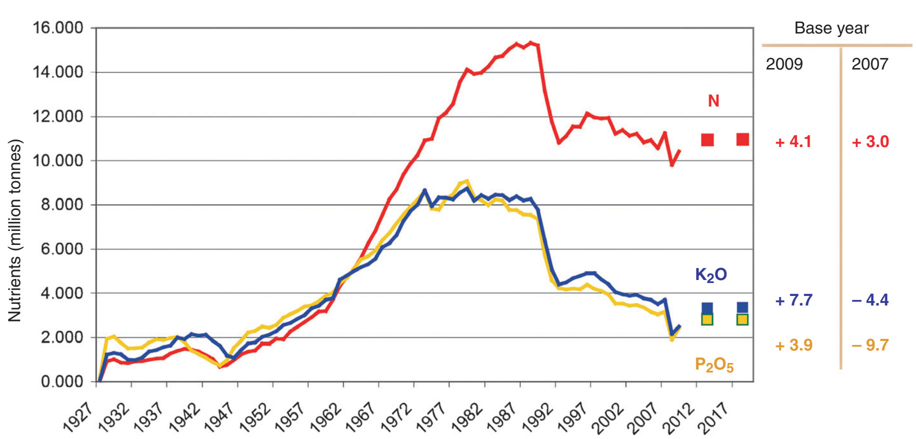

Figure 3.2 Total fertilizer nutrient consumption in the EU-27 countries in the period 1927–2009, and predicted trend in fertilizer nutrient use until 2019. Two different predictions are given, based on either the reference years 2007–2009 or 2005–2007 (EFMA, 2009).

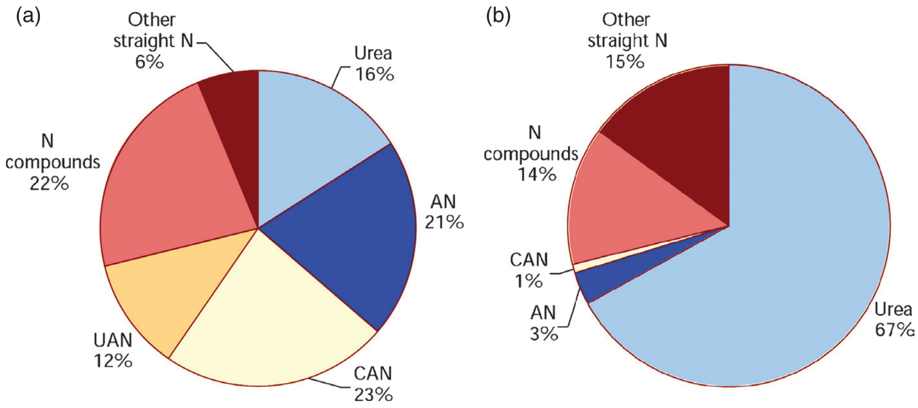

Figure 3.3 Current consumption of different sources of fertilizer nitrogen in (a) EU-25 plus Switzerland and Norway and (b) developing countries (EFMA, 2003). AN = Ammonium nitrate, CAN = Calcium ammonium nitrate, UAN = Urea ammonium nitrate, N compounds = compound fertilizer, containing N together with P and/or K as well as other macro- and micronutrients.

fertilizer-N use, wheat is the most important crop in the EU, followed by grassland and barley. Although oilseed rape and sugar beet have the highest N rates, their crop area is smaller. Based on this information the economic benefit of N will be discussed later in more detail for wheat, oilseed rape and grassland. Emphasis will be given to regional differences within Europe.

Expected future trends in fertilizer Nitrogen consumption for major crops in the EU

Forecasts of developments in European (for the EU-27 countries) fertilizer demand over the next 10 years are created annually by Fertilizers Europe (formerly European Fertilizer Manufacturers Association, EFMA). The forecasts are based on national prognoses, in a standardized, upward procedure, where fertilizer consumption is evaluated by assessing area and nutrient application rates for each crop in all member states, and held against economic developments, i.e. market prices for agricultural inputs and products.

On average over the last three cropping years (2007–2009) in the EU-27, fertilizers containing 10.5 Gt of N have been applied to 135.3 million ha of farmland each year (46.1 million farmable hectares are not fertilized, which include 36.5 million hectares of unfertilized grasslands). By 2018/2019, the forecasters expect the fertilizer N consumption to reach 11.0 Gt of nitrogen (an increase in N consumption of +4.1%, Figure 3.2), applied to 133.6 million ha (EFMA, 2009). However, this expected increase is not evenly distributed geographically, most of the increase (+17%) is expected in the new EU member states (termed EU-12), with very marked increases in e.g. Bulgaria (+25%) and Romania (+55%). In the old EU member states (termed EU-15), the majority of countries predict a decline (−1% to −12%) in fertilizer N consumption until 2019, with only Spain and Sweden expecting increases above +10% (EFMA, 2009).

For the major crops produced in Europe, the expectation is that N demand for wheat, coarse grains (other cereals) and oilseeds will increase, whereas fertilizer N input for sugar beets, potatoes, fodder crops and grasslands are expected to decrease until 2019 (Figure 3.4).

3.2.2 Organic manure N inputs

Nitrogen in manure is applied in the form of stored manure collected in animal housing and manure deposited by grazing animals in the field. The input of manure-N to crops in the European countries varies from 15 to 225 kg/ha of agricultural land per year (Figure 3.5). In comparison, the average use of mineral fertilizer amounts to between 15 and 140 kg/ha of agricultural land per year (Figure 3.5). Total national nitrogen inputs (incl. manure N) to agricultural land range from about 40 kg/ha of agricultural land in Romania to 365 kg/ha in the Netherlands.

The amount of manure-N applied to specific crops in the EU is not well known. It varies between countries, depending on livestock systems, manure type, crops, rotations and their distribution.

Manure from cattle, sheep and goats (ruminants) produced during grazing is deposited on grasslands, while manure from animal housing and storage is mainly applied to fodder or roughage crops (grass, silage maize). Pig and poultry manure is generally used on non-fodder (feed, food, fibre, fuel) crops, as these are generally grown on farms without ruminant livestock. Velthof *et al.* (2009) distinguish between three types of non-fodder crops, viz. those with high manure application rates (potato, sugar beet, barley), crops with moderate rates (wheat, rye, oat, grain maize) and crops where generally no manure is given (fruits, citrus, oil crops).

3.2.3 Biological N fixation

Globally, leguminous crops, mainly soybean and peanut, cover about 10% of agricultural land (Smil, 1999). Galloway *et al.* (1995) and Smil (1999) estimated global N_2 fixation for cultivated agricultural systems, i.e. excluding the extensive tropical savannas, at 43 Tg (range 32–53 Tg) and 33 Tg (range 25–41 Tg) annually. Herridge *et al.* (2008) calculated N_2 fixation by the coarse grain legume–rhizobia symbioses at 21 Tg N annually and by the forage and fodder legume–rhizobia symbioses to range from 12 to 25 Tg, annually.

In Europe, the main N fixing crop species is clover grown together with grass as a crop for feed purposes (grazing and

Table 3.2 Average annual, minimum, maximum and cumulative fertilizer N-use for European crops in EU-27 (EFMA 2005–2007).

Crop	Average kg/ha	Range (min–max) kg/ha	Crop area million ha	N use = crop area × avg. N-rate (million kg)
Oilseed rape	148	50–195	6.1	884
Sugar beet	123	50–160	1.9	228
Wheat	113	25–200	25.9	2902
Grain maize	106	26–200	9.0	958
Potato	98	40–185	2.2	218
Barley	88	15–145	13.9	2011
Grassland	69	10–170	30.5	2075
Silage maize	65	10–126	4.7	304
Rye, triticale, oats, rice	64	10–110	8.7	549

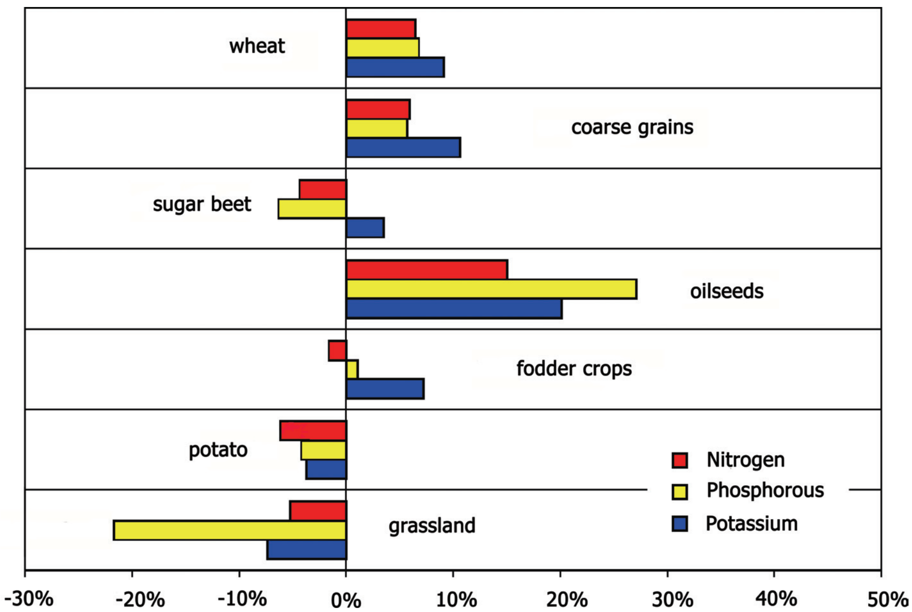

Figure 3.4 Forecast changes from 2009 to 2019 in fertilizer N, P and K use by crop sector (taking account of both projected changes in area and yields of the crops) in the EU-27 overall (EFMA, 2009).

roughage). Using various modelling approaches, de Vries *et al.* and Leip *et al.* (2011, Chapters 15 and 16, this volume) estimated that the biological N fixation in European agriculture is in the range of 0.8–1.4 Tg N annually, out of a total annual N input of 20.8–26.2 Tg. Hence biological N fixation only accounts for 3%–5% of the N inputs to agricultural land in Europe.

3.2.4 Efficiency of nitrogen inputs

Mineral fertilizer

Mineral fertilizer N can in principle be applied at the time and location that is optimal for crop uptake. This should lead to potentially high N use efficiencies. However, in practice many factors may reduce the actual N use efficiency. There are many ways to define and measure N use efficiency. Here, two different approaches are applied:

(1) the apparent recovery efficiency (NUE_a), which is the increase in N uptake (or total biomass) divided by the amount of N applied

$$[\text{N-uptake}_{\text{N-fertilizer-rate(X)}} - \text{N-uptake}_{\text{No-N-fertilizer}}] / \text{N-fertilizer-rate(X)};$$

(2) the direct recovery efficiency (NUE_d), which is the amount of labelled N that is taken up in a crop (usually only above-ground material) following application of ^{15}N labelled fertilizer

$$^{15}\text{N-uptake}/^{15}\text{N-fertilizer-rate(X)}.$$

The direct recovery efficiencies are generally smaller than the apparent recovery efficiencies because some of the applied N is incorporated into the microbial biomass N and subsequently becomes incorporated into the soil organic matter.

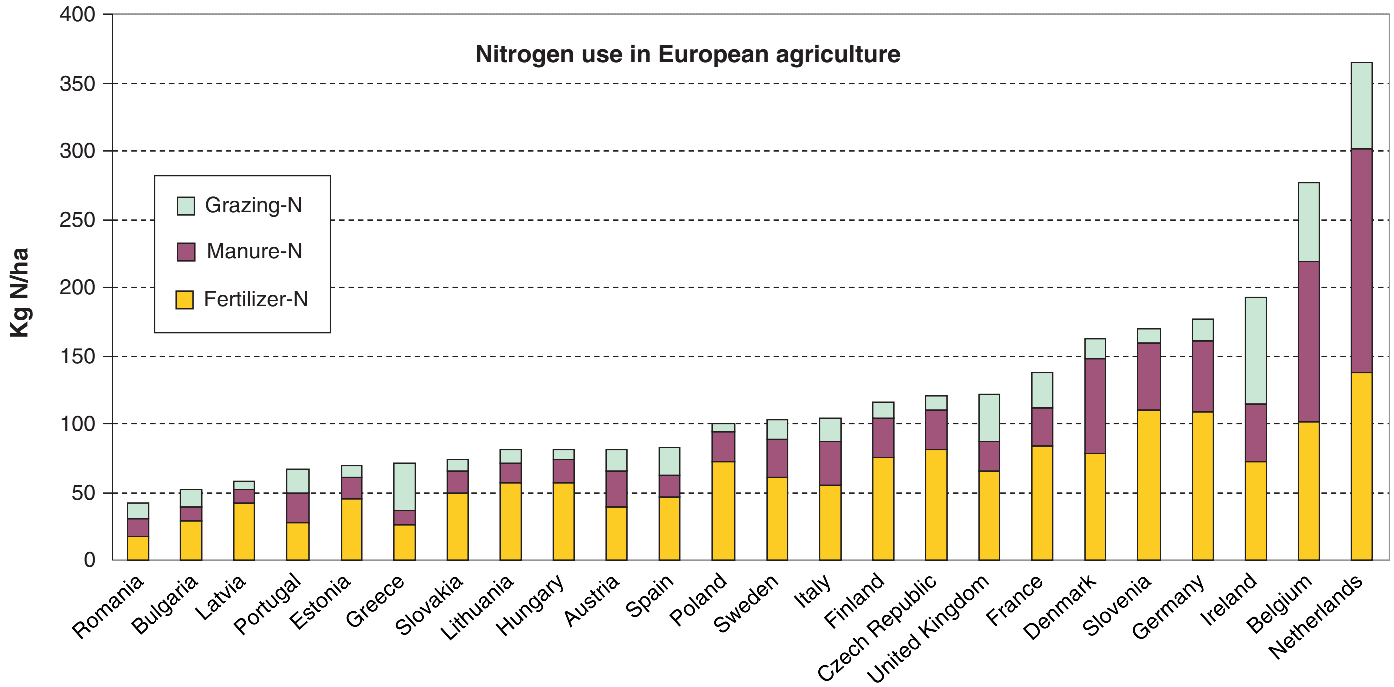

Figure 3.5 Average annual nitrogen inputs in fertilizer and manure (applied and deposited during grazing) to agricultural land in the EU (Luxembourg, Malta and Cyprus omitted). Fertilizer data for 2007–2008 based on EFMA (2009). Manure data are based on data for 2000 from Velthof *et al.* (2009).

Currently, worldwide recovery of N fertilizer (NUE_a) in cereal crops is on average 30%–50%. Higher values, exceeding 60%, have been reported for winter wheat, e.g. in Denmark and in the UK (Sylvester-Bradley and Kindred, 2009) when crop management is optimal and N applications are balanced against expected yield and soil fertility status. In contrast, average N fertilizer recovery in cereals in China may be as low as 30%–35%, mainly due to unbalanced and excessive fertilization, leading to large N surplus and N losses (Vitousek *et al.*, 2009). Typical nitrogen recovery efficiencies (NUE_a) in research plots are about 40%–50% for cereals when defined based on grain N yield, increasing to 60%–70% when based on total aboveground N uptake (Chien *et al.*, 2009).

Direct recovery efficiencies (NUE_d) of mineral fertilizer N applied in autumn in temperate humid climates have been measured at 11%–42% for winter wheat in Great Britain (Powlson *et al.*, 1986a). For springtime applications, NUE_d increases to 42%–78% illustrating the effect of improved timing of the application and synchrony with crop N uptake (Powlson *et al.*, 1986b; Pilbeam, 1996).

Experiments with ^{15}N-labelled fertilizers applied to wheat have shown higher direct recovery efficiencies (NUE_d) in humid than in dry environments. However, the retention of residual ^{15}N in the soil increases with increasing climate dryness (Figure 3.6). In a review of a large number of wheat experiments across various climates, ranging in annual rainfall/evaporation ratios from 0.14 (Israel) to 1.32 (Alabama, USA), Pilbeam (1996) found a significant positive correlation between the annual rainfall/evaporation ratio and N uptake efficiency (Figure 3.6). Hence, owing to unfavourable growth conditions in a drier climate, N uptake efficiencies tend to be lower than under humid conditions, but the larger proportion of unused fertilizer N apparently remains in the soil after harvest. The loss of fertilizer N seemed independent of climate and averaged 20%, with the main loss pathways thought to be dominated by leaching loss in humid climates and gaseous loss in arid climates. However, under practical conditions, fertilizers prone to gaseous loss, e.g. urea, may lose up to 20%–30% by NH_3 volatilization immediately following application in warm climates. Postharvest losses of residual fertilizer N are usually small (less than 5%), indicating that the soil nitrate pool which is susceptible to leaching during autumn and winter in humid environments mainly originates from mineralization of organic nitrogen. Thus nitrate leaching typically represents an indirect rather than a direct loss of applied fertilizer N, having first been converted to organic matter.

Fertilizer nitrogen use efficiency in the EU-27 countries, i.e. the member states of EU as of 2007, varies between countries both due to soil and climatic differences, but also because dominant crop species and fertilization practices differ significantly from one country to another. If cereals are taken as a main common denominator, a wide range of yields are observed, both within the EU-15 (old member states) and the EU-12 (more recent members). In Figure 3.7, cereal yield is expressed as a function of the annual nitrogen application rate per ha of arable land in each of the EU countries. The quantity of grain produced for an additional quantity of nitrogen, commonly referred to as the agronomic efficiency (slope of regressions in Figure 3.7), appears somewhat higher for the EU-15 than for the EU-12 countries, but the difference is not significant. The average agronomic efficiency for all EU-27 countries is around 41 kg grain per kg N applied.

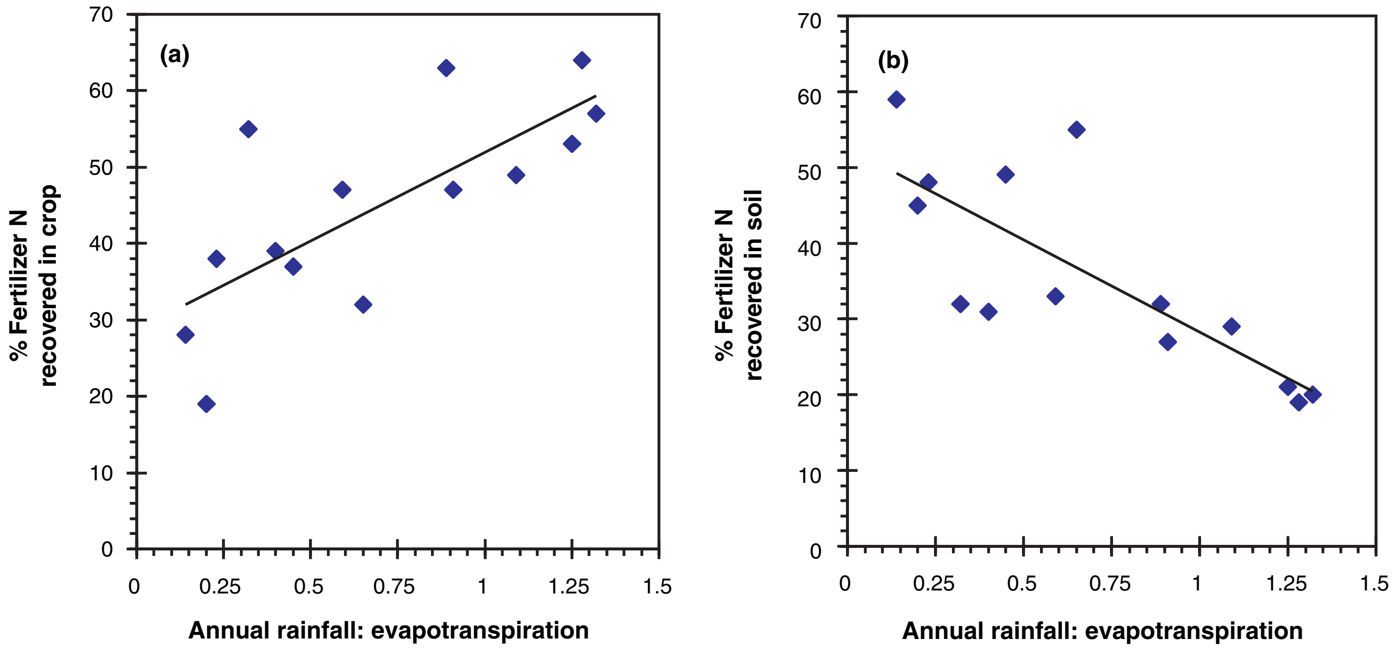

Figure 3.6 Relationship between the precipitation/evapotranspiration ratio and the recovery of ^{15}N-labelled fertilizer N in (a) the crop and (b) the soil at harvest for wheat grown in different locations (redrawn from Pilbeam, 1996).

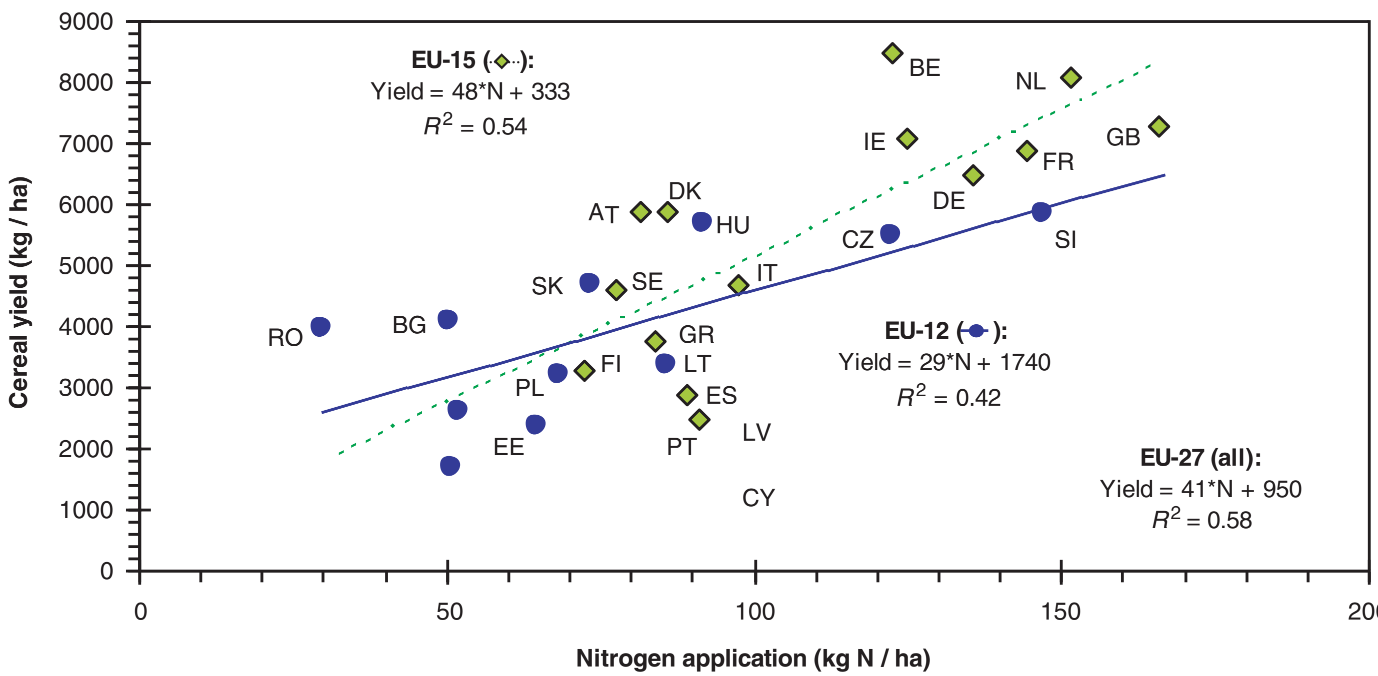

Figure 3.7 Annual cereal crop yield vs. nitrogen application in the EU-27 countries. The slope of the regression lines, i.e. kg grain harvested per kg fertilizer N applied, is the apparent fertilizer N use efficiency, also termed the agronomic N efficiency. The slope does not differ significantly between EU-12 and EU-15 countries. Data from EFMA (2007).

In order to further improve the recovery efficiency of mineral N fertilizers focus should be on (i) improved synchrony between fertilizer N and crop demand, i.e. the timing, (ii) site-specific fertilization to take into account spatial heterogeneity on field-level, i.e. the rate and place, and (iii) possibilities for taking into account year-to-year weather variations affecting crop growth and soil N mineralization and (iv) reduce risk of fertilizer N loss, e.g. through rapid soil incorporation (if possible) or the use of inhibitors of urea hydrolysis (to minimize ammonia volatilization, most relevant for surface application) or nitrification (to reduce leaching of nitrate).

The most obvious way to improve the synchrony between crop N demand and N supply is to split the N application into several single dressings. Doing so allows the total N supply to be readjusted according to the actual growing conditions during the year of cultivation. Analysis of soil and plants can further help the farmer to exactly target the N application to the crop requirements.

Slow-release fertilizers have been developed which contain N in forms that delay the initial availability or extend it over time, ideally to match the uptake by the crop. These fertilizers typically consist of urea-aldehyde polymers (urea-formaldehyde, isobutyliden-diurea or crotonolidendiurea) which are compounds with a very low solubility in water. This is in contrast to the so-called controlled-release fertilizers, which are produced through modification of urea, enabling them to release nitrogen over a given period (up to 12 months) through a coated surface or through an encapsulating membrane. It must be noted that the costs of controlled-release or stabilized fertilizers are significantly higher than those of conventional fertilizers. Thus, their main uses have so far been restricted to high value crops, specific cultivation systems and non-agricultural higher-value sectors (horticulture, nurseries, greenhouses, etc.).

Urease inhibitors are used to reduce ammonia volatilization from urea (Chien *et al*., 2009). More than 14 000 mixtures of compounds with a wide range of characteristics have been tested and many patented as urease inhibitors. Lately, focus has been on the urease inhibitor N-(n-butyl) thiophosphoric triamide (NBPT) and other inhibitors of the phosphoroamide family, including 4-methyl-2-nitrophenyl phosphoric triamide and 2-nitrophenyl phosphoric triamide. These compounds have been widely tested and in many cases reported to significantly increase N recoveries from urea (Watson *et al*., 2008; Turner *et al*., 2010). However, urease inhibitors cannot completely control NH_3 loss when urea is surface applied to soils because the inhibitory effect depends on soil physical and chemical characteristics and also on environmental conditions. The urease inhibitors available so far can prevent urea hydrolysis for at most 1 or 2 weeks, during which time the fertilizer should ideally be incorporated into the soil by water (rain or irrigation) or mechanical methods. In addition, the price of NBPT may exceed the payback and hence limit the economic incentive for using it.

Stabilized fertilizers are associated with nitrification inhibitors such as ammonium thiosulphate, thiourea, dicyandiamide, nitrapyrin and 3,4-dimethylpyrazole phosphate. Nitrification inhibitors are chemical compounds that delay bacterial oxidation (nitrification) of ammonium nitrogen. The objective is to preserve applied ammonium nitrogen in its original form, which is stable in the soil, and to slow its conversion to nitrate. This temporarily lessens the proportion of nitrate in the soil thereby reducing potential leaching losses or formation of N_2O (Irigoyen *et al*., 2006; Akiyama *et al*., 2010).

Crop parameters influencing N uptake and the dry matter production per unit absorbed N are obviously also important for maximizing fertilizer N recoveries. In-season crop monitoring through ground-based reflectance sensors, leaf chlorophyll meters or aerial/satellite imaging can be used to target crop N requirements. This can be accompanied by selection of N-efficient cultivars. Specific examples of traits which are of particular value for increasing nitrogen recovery in feed wheat cultivars are (Figure 3.8): (i) increased root length density at depth, (ii) a high capacity for N accumulation in the stem, potentially associated with a high maximum N-uptake rate, (iii) low leaf lamina N concentration, (iv) more efficient post-anthesis remobilization of N from stems to grain, but less efficient remobilization of N from leaves to grain, both potentially associated with delayed senescence, and (v) reduced grain N concentration. In cultivars for bread-making, high nitrogen use efficiency may in addition be associated with specific grain protein composition.

Organic manures

In organic manures, a significant proportion of the N is organically bound. This organic N pool mineralizes slowly into ammonium and subsequently nitrate in the soil and only a part becomes available for plant production in the year of application. In addition, the portion of N_r in organic manures that is not organically bound is present as ammonium, implying risk for a high loss through ammonia volatilization. Consequently, crop use efficiencies of manure N are normally lower than that of mineral fertilizer N. The lower the proportion of organic N in the manure (as in liquid manures, e.g. slurry or urine), the faster and greater crop uptake (utilization) of manure N can be expected, as long as large losses of ammonia are avoided. The organically bound N in manure contributes to the N pool in the soil and this becomes plant-available via mineralization in subsequent years (Schröder *et al*., 2005; Vellinga *et al*., 2010). Proper determination of the true N use efficiency therefore requires long-term trials.

The plant-availability of N in manure within the year of application is often expressed as the 'Nitrogen Fertilizer Value' (NFV) or 'Mineral Fertilizer Equivalent' (MFE). These parameters are determined by reference to crop mineral fertilizer N response, with 100% representing equivalent crop utilization of manure and mineral fertilizer N within the first cropping season after application. Owing to the content of organic N in manure, MFE values normally range between 20% and 80%, depending on the type of manure (proportion of organic N), the crop, the application time (autumn application resulting in higher leaching losses than spring application) and application methods (surface application resulting in higher ammonia losses and lower MFE value than injection into the soil).

With strict regulations on manure application methods in some EU countries (e.g. Denmark and the Netherlands), fertilizer efficiency of manure N has generally increased in recent years as evident from the MFE values in Table 3.3 and also reported by Birkmose (2009). Consequently, the use of N in mineral fertilizer has declined, in Denmark by as much as 50% since 1990. A monitoring programme shows that the Danish nitrate leaching in the same period was reduced by 41% (Grant *et al*., 2009), and the emission of ammonia by 42% (Gyldenkærne and Mikkelsen, 2007). However, in order to achieve such improvements, substantial investments have been

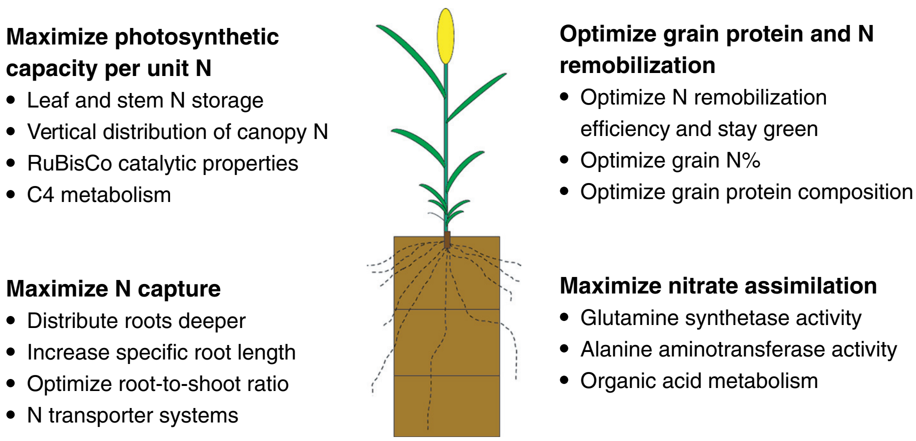

Figure 3.8 Parameters important for crop N benefits (modified after Foulkes *et al*., 2009 and Reynolds *et al*., 2009).

made in low emission stables, manure storage facilities and low emission spreading equipment.

The long-term effects of management practices on soil quality will also have an important influence on the N use efficiency of the entire agro-ecosystem. Soil organic matter content is a key measure of soil quality and soils that sequester carbon also sequester N, resulting in greater indigenous N supply and a reduction in N fertilizer requirements. Therefore, management practices which increase soil organic matter will generally provide efficiency benefits over the long term.

3.3 Nitrogen effects on crop productivity and quality

Nitrogen is one of the most important limiting factors for biomass productivity in terrestrial ecosystems. The stimulating effects of N on plant growth are due to a direct role of N as a building block in proteins, nucleic acids and pigments (chlorophyll). Roughly three quarters of all N in the leaf is contained within the chloroplasts (Dalling, 1985), predominantly as a constituent of the enzyme Rubisco which catalyses fixation of carbon dioxide. The N supply affects the biosynthesis of the phytohormone cytokinin, which functions as a growth promoter. It is via cytokinin that ample nitrogen supply stimulates growth and early establishment of the leaf area which is required for light (energy) interception, photosynthesis and biomass production (Marschner, 1995; Wang and Below, 1996).

3.3.1 Crop yield responses to nitrogen

Nitrogen fertilizers have a decisive influence on the yield of arable crops. Since the days of von Liebig in the nineteenth century up to the present day, countless experiments have been carried out to determine the crop yield response to N. Response curves generally show an increase in crop production with increasing N supply up to a certain level, provided other production factors such as water and other nutrients are sufficiently available (see also Table 3.1). Crop N demand is the product of plant dry weight and the minimum N concentration in the dry matter needed to obtain maximum growth. The fact that yield response to N application typically follows a convex curve reflects that yield responses per extra unit of N applied become smaller and smaller as the N quantity increases. This diminishing return is due to the fact that the efficiency of light interception within the canopy decreases as more and more leaves get shaded by the above leaves in the canopy. Various crops show a negative response to N at high levels because of effects like lodging (cereals), increased incidence of pests, decreased quality (sugar content in sugar beet, oil content in oilseed rape).

Wheat field trials in north-western Europe (Belgium, UK, Ireland, Denmark, France, Germany, the Netherlands) show maximum grain yields in the range of 9–11 ton/ha. However, actual farm grain yields in this region are often 2–3 ton/ha lower. Yields in eastern and north-eastern Europe are about the same, at around 4 t/ha. Especially yields in southern Europe under rain-fed conditions are much lower (trials: 2–5 t/ha), whereas actual yields are about 2.5 t/ha. However, published results of field trials for wheat, oilseed rape and grassland in southern and eastern Europe are rather rare (Shiel *et al*., 1999; Sidlauskas and Bernautas, 2003; Barłóg and Grzebisz, 2004; Lopez-Bellido *et al*., 2007; see also supplementary material to Chapter 22 of this volume, Brink *et al*., 2011).

Different crop production models (mathematical functions) have been developed and tested for calculation of the relationship between crop yield and nitrogen supply or fertilization rates. This of course implies uncertainties in terms of model choice, annual nitrogen response variations and parameter estimation (Henke *et al*., 2007). A number of these models has been analysed, showing advantages and disadvantages (e.g. for corn: Cerrato and Blackmer, 1990; winter wheat: Webb *et al*., 1998; Makowski *et al*., 1999; Gandorfer, 2006). The most commonly used crop yield response functions used in north-west European agriculture are the linear with plateau (LP), the quadratic (Q) and the exponential (EXP) type. An example of these, fitted to the same data, can be seen in Figure 3.9a. The quadratic and exponential functions can be combined with linear functions to construct quadratic functions with plateau

Table 3.3 Average Mineral Fertilizer Equivalent (MFE) value of N in manure for different countries in the EU as affected by animal manure type. Values represent estimates from field experiments in five different EU countries as used by advisory systems for fertilization planning (ten Berge and van Dijk, 2009)

Type of manure	Crop, application time	Nitrogen MFE value (% of manure total N)				
		NL	FL	DE	DK	FR
Cattle slurry	Arable land, spring, maize/ pot./beets	50–55	55	70	55–70	55
	Arable land, spring, winter wheat	40	55	70	45–55	
	Grassland, before 1st cut	45–50	55	70	45–50	50–60
	Excreted on pasture			25		
Pig slurry	Arable land, spring, maize/ pot./beets	70–75	65	60	70–75	60–75
	Arable land, spring, winter wheat	55	65	60	65–70	60–70
	Grassland, before 1st cut	45–55	65	60	60	50–65
Solid cattle manure	Arable land, spring, maize/ pot./beets	30	30	60	45	15–30
Solid chicken manure	Arable land, spring, maize/ pot./beets	50–55	55	50	65	45–65
Liquid fraction	Arable land, spring, maize/ pot./beets	85–90	80–90		90	
after separation	Arable land, spring, winter wheat	70	80–90		85–90	
	Grassland, before 1st cut	65–75	80–90		75–80	
Solid fraction after separation, cattle	Arable land, spring, maize/ pot./beets	25	25		55	
Solid fraction after separation, pigs	Arable land, spring, maize/ pot./beets	50	35		55	
Compost	Arable land, spring, maize/ pot./beets	10	10			10–15

Note: NL = the Netherlands, FL = Flanders (Belgium), DE = Germany, DK = Denmark, FR = France.

(QP) or linear-exponential functions (LEXP), which have a distinct maximum yield level, whereas the EXP function has no maximum, and the quadratic function yield declines at high N input rates. Differences in economic optimal N application rate (EONR, see further details below) resulting from applying different crop response functions can be substantial (e.g. 60 kg/ha in Figure 3.9a). Although the degree of model fit to yield data should be an important criterion, it is not always clear why a certain model is given preference over other models (Cerrato and Blackmer, 1990).

The yield at zero N rate (Figure 3.9) is caused by the crop response to N originating from atmospheric deposition, biological fixation (in case of legume–grass mixtures) and from soil mineral N (SMN), which is also a result of the history of the plots (N-input and uptake efficiency of preceding crops). In a number of countries, among others the UK, Germany, Belgium, the Netherlands and Denmark, the estimation of SMN is an integral part of the fertilizer recommendation systems. Figure 3.9b illustrates the influence of long-term absence of fertilizer or manure N input on the soil N supply capacity. In the nil fertilizer N plot of the long-term (>150 years) trials, crop N uptake and removal in grain was only 26 kg N/ha, whereas in the short-term trials with normal fertilization in preceding years this was around three times higher, 74 kg N/ha, reflecting a higher SMN and N mineralization capacity of the soil. In regions with very low fertilizer N-input, soil mineral N may often be the major source of N for crop yield and uptake.

It is clear from Figure 3.9b, that if the N use efficiency is calculated as apparent N recovery (NUE_a) at economic optimal fertilizer N rate (EONR) with reference to the unfertilized plot ([N removal at EONR – N removal without fertilizer]/ EONR),

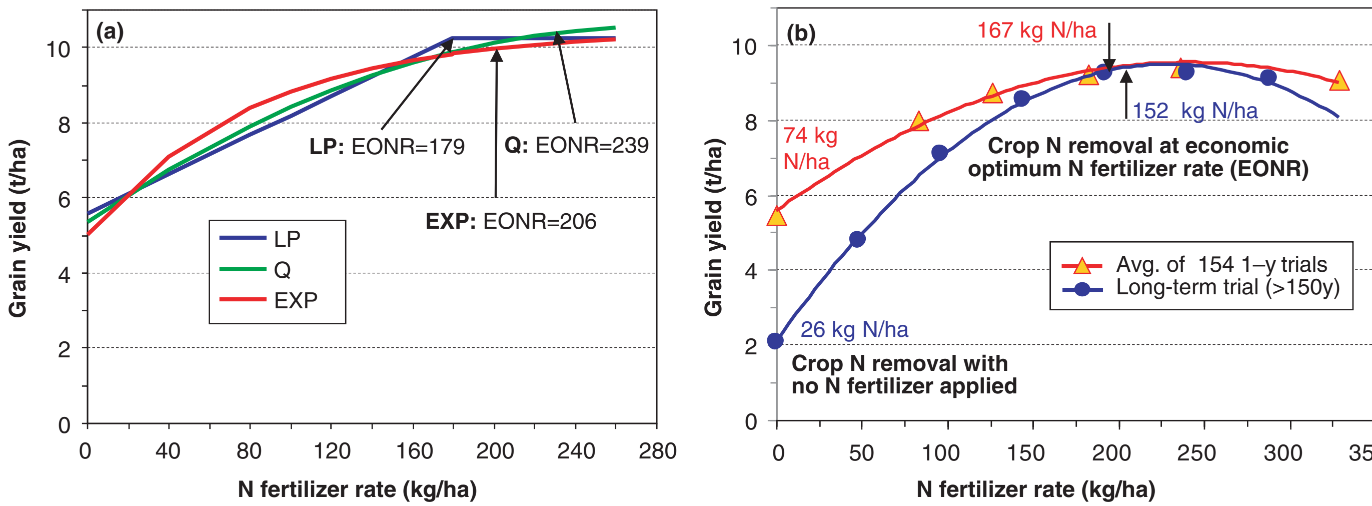

Figure 3.9 (a) Examples of mathematical functions commonly used to express crop yield responses to increasing annual nitrogen application (LP: linear with plateau, Q: quadratic, EXP: exponential) and the resulting different economically optimal fertilizer N rates (EONRs) for winter wheat in Germany (after Gandorfer, 2006). (b) Winter wheat grain yield response to increasing fertilizer N application in short-term (1-year) trials (average of 154 individual experiments) and in a long-term trial with the same N application rates for many years (>150 years). Numbers (kg N/ha/yr) indicate N removal with grain at either no fertilizer N application or at EONR (indicated by arrows), respectively (calculations based on Broadbalk long-term trial in Rothamsted, UK, and Yara field trials, F. Brentrup personal communication).

the NUE_a is somewhat lower (51%) from the short-term (1-year) trials than from the long-term trial (66%). However, this is because a small part of the mineral N applied to a crop in previous years will be immobilized as soil organic N and thus be available for subsequent years' crop. Therefore, interpretation of NUE from short-term trials should be done with consideration of this long-term effect of fertilization level.

Field trials show a large year-to-year variation in yield response, which leads to different economic optimal N application rates. As an example for winter wheat in Germany, economic optimal N application was found to vary by as much as 85 kg/ha (Henke *et al.*, 2007). Similarly, in a review of a very large number of N response trials in winter wheat and spring barley from different combinations of season, site, and cultivar in the UK (Sylvester-Bradley and Kindred, 2009), economic optimal N rates at a N price:grain price ratio of 5 were found to vary by more than 200 kg/ha for winter wheat and up to 150 kg/ha for spring barley (Figure 3.10). These data confirm that there is no direct relationship between crop yield and economic optimum N fertilizer rate. The presence of this wide range affects both the N-recommendation and the farmers' decision to adjust the N-rate, as future weather conditions are always unknown. Farmers can react to this challenge, for example, by splitting their nitrogen application into several dressings. Other sources of variation in crop response are soil conditions and crop cultivar.

For horticultural crops such as vegetables, yield response to N application also varies considerably, both between fields and years of the same crop, but in particular between species. As illustrated in Figure 3.11, yield typically increases with N application rate until a plateau, where no further yield increase is achieved, but also no yield decline in contrast to cereals. It is obvious that optimal N levels vary greatly between a crop like white cabbage, with a very large N uptake capacity, deep roots and a long growing season, and a crop like lettuce, with a rapid growth, but shallow roots and a short growing season. In order to avoid excessive N application in vegetable cropping, and hence leaching or gaseous N losses to the environment, monitoring of soil mineral N supply is crucial in order to adjust the fertilizer N input accordingly. However, usually the cost of fertilizer is negligible compared to the often very high value of a vegetable crop, giving relatively little incentive for the farmer to limit fertilization to the economic optimum.

3.3.2 Assessment of economic optimal N-rate

The costs of nitrogen in proportion to the total production cost of agricultural crops such as cereals ranges from 20% to 30% of the variable production cost (Zimmer, 2008), thus constituting a significant share of the total costs. For high-value horticultural crops, however, the N fertilizer costs may amount to only a few percent; for instance for edible potato it ranges between 2% and 9% of the variable production costs, and between 1% and 4% of the total production costs. Generally speaking, a farmer will strive for maximization of profit. Farmers should try to meet the economically optimal N application rate, but in practice they tend to assure adequate input of nitrogen, as this increases the chance of economical return on investments for other production factors. This may lead to unnecessary application of nitrogen fertilizer, e.g. in the USA amounting to 20%–35% of total N at a cost up to 50 €/ha (Sheriff, 2005). Overuse of N-fertilizer is also promoted when farmers or their contracts with purchasers set yield targets before the growing season. In this case, the N application rate is adjusted to the target yield without being able to properly consider other production factors like availability of other nutrients, water, pest control, etc., which have to be adequate to achieve the target yield. As Figure 3.10 shows, there is no relationship between yields and economic optimum fertilizer rates.

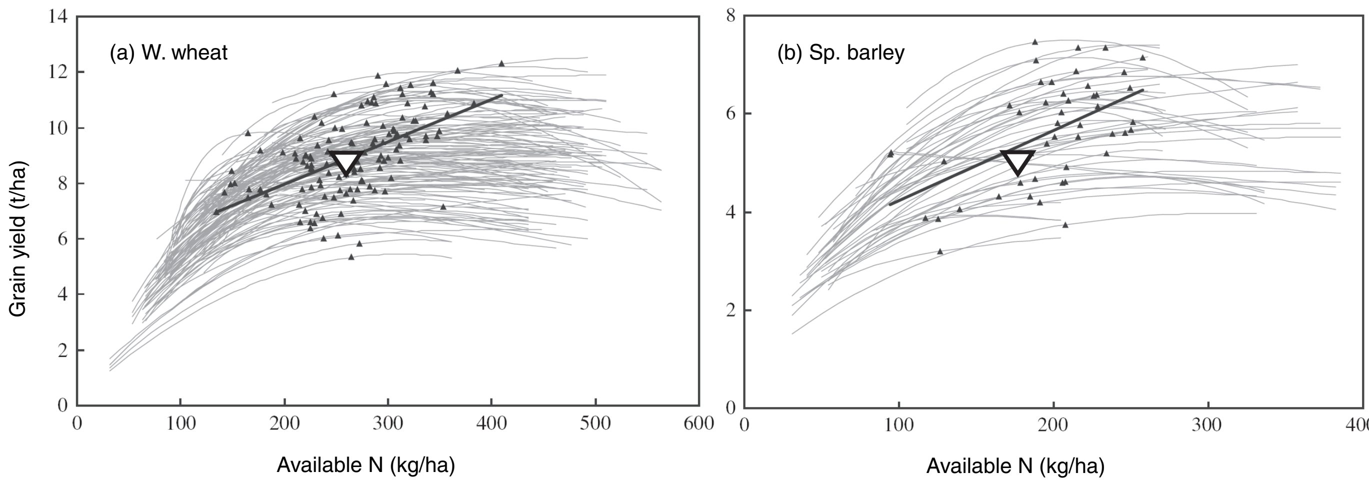

Figure 3.10 Fitted responses of grain yield to available N (soil N supply through mineralization plus fertilizer N applied per year) for (a) winter wheat (129 response curves) and (b) spring barley (47 response curves); from different combinations of season, site, and cultivar in the UK. Economic N optima (at fertilizer N:grain price ratio = 5) for each response curve are indicated by small triangles, mean of all economic optima with large triangle (Sylvester-Bradley and Kindred, 2009).

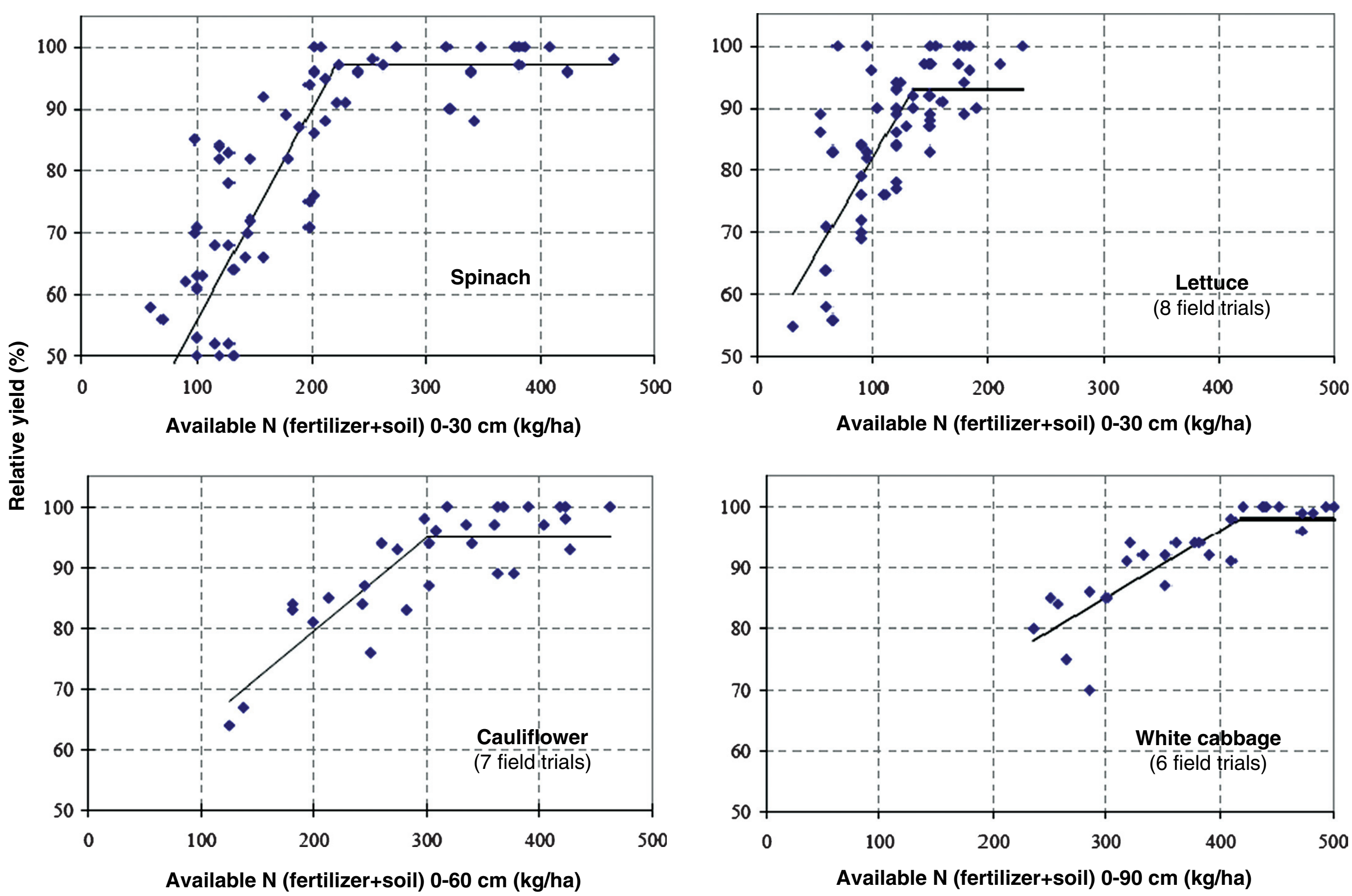

Figure 3.11 Examples of vegetable N responses for various vegetable crops in field trials from Germany (Feller *et al.*, 2001).

There is no standard approach to determine the economic value of N at the farm level. The parameter to determine the appropriate N level is the 'economic optimal N-rate' (EONR). This is the N-rate where the marginal financial return of the harvested crop equals the marginal cost of N, i.e. where the slope of the tangent of the yield response curve is equal to the reciprocal of the price ratio (see Figure 3.12). Nitrogen fertilizer application should not target the maximum crop yield, rather it has to target the economic optimum crop yield.

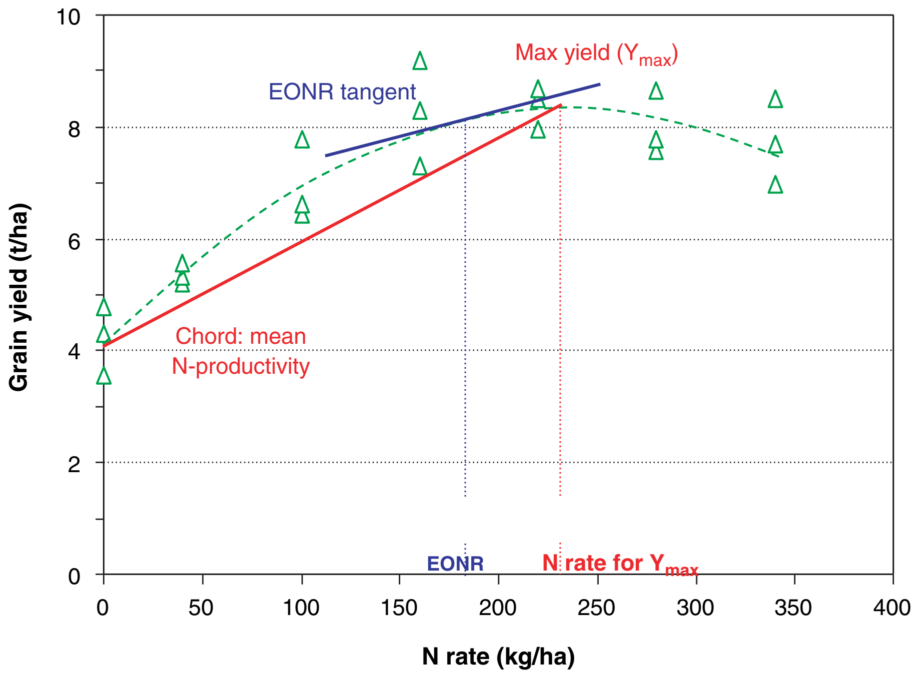

Figure 3.12 Illustration of the concept of economically optimal N rate (EONR). The slope of the tangent to the yield response curve represents the marginal yield increase due to additional annual fertilizer N application. EONR is where the slope of this tangent is equal to the fertilizer N to grain price ratio.

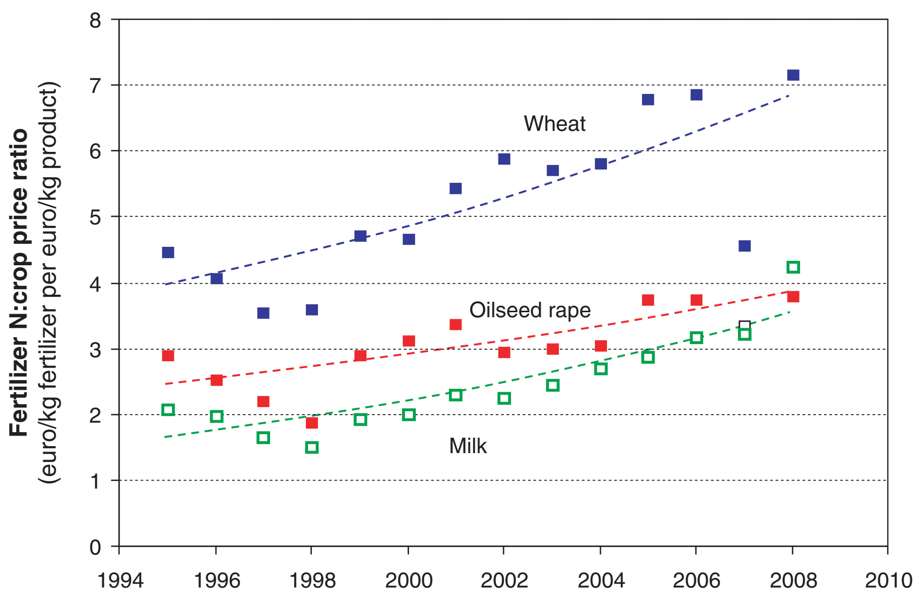

Figure 3.13 Trend of the price ratio of fertilizer nitrogen (calcium ammonium nitrate; LEI, 2009) over crop price for wheat and oilseed rape, using data for the UK, Denmark, Germany, Czech Republic and Spain (EUROSTAT, 2009) and for milk (data from the Netherlands; LEI, 2009).

The economic optimum N-rate (EONR) depends on the ratio of prices of mineral fertilizer N and of crops. The prices of fertilizers and crops may be somewhat correlated, as increased crop prices will increase the demand for fertilizer, and conversely, increasing energy prices will tend to increase crop prices. However, the general tendency has been an increase in this price ratio over the past couple of decades (Figure 3.13). This trend is largely a result of increasing energy prices, while crop prices have been stable or decreasing and means that the costs of N fertilizer are becoming an increasingly important control on rates of N application.

The economic return on N (ERoN) is not a standard parameter and is defined here as the ratio of the slope of the chord of the response curve (the mean N-productivity, kg grain per kg N) connecting yield at N = 0 and the maximum yield (see Figure 3.12), and the fertilizer:crop price ratio. Jenkinson (2001) was one of the few who assessed the economic value of fertilizer N in this way. Using the results of the Broadbalk continuous wheat experiment at Rothamsted, he concluded that the investment of £66 on fertilizer generated an extra grain yield of £367, which corresponds to an ERoN value 5.6. Yield response curves depend on soil, climate, crop variety, management practices, and consequently also values of EONR and ERoN derived from such curves.

In Figure 3.14, we have estimated the gross economic return on nitrogen fertilizer (ERoN) for winter wheat and oilseed rape

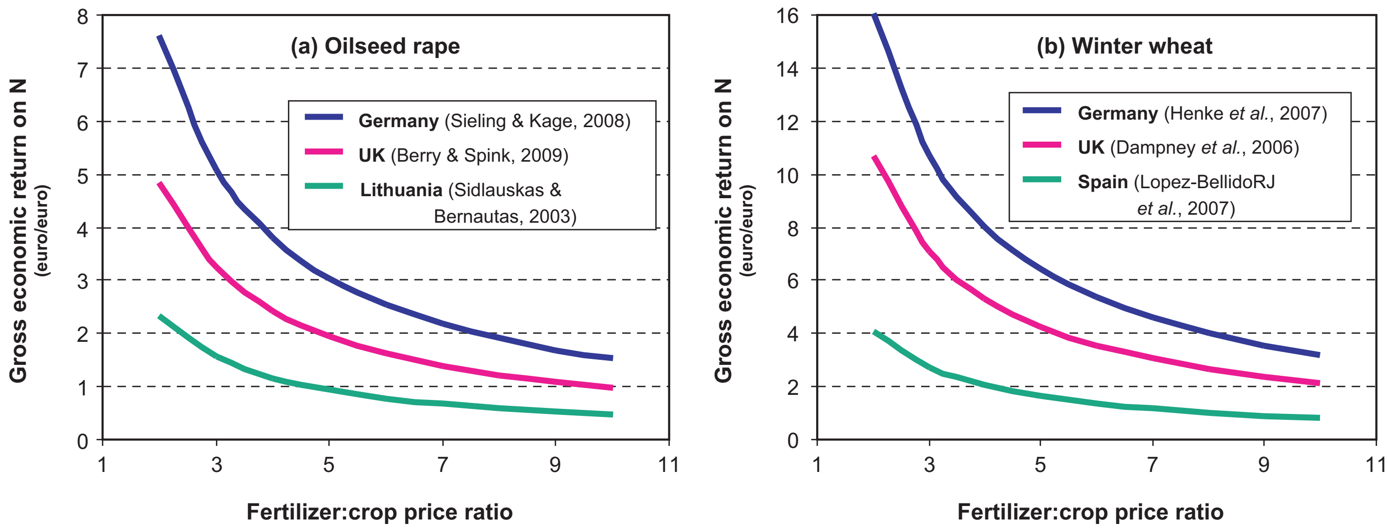

Figure 3.14 Gross economic return on nitrogen fertilizer (ERoN) for oilseed rape (a) and winter wheat (b) as a function of fertilizer:crop price ratio (€/kg N per €/kg crop). Results based on N-response curves from field trials and at actual mean national N-rates (EFMA, 2009).

as a function of different price ratios between fertilizer and crop. The calculations are based on selected yield data for cultivation of winter wheat in Germany (Henke *et al.*, 2007; Rathke *et al.*, 2005; Sieling and Kage, 2008), Spain (Lopez-Bellido *et al.*, 2007) and the UK (Dampney *et al.*, 2006), and for oilseed rape in Germany, the UK (Berry and Spink, 2009) and Lithuania (Sidlauskas and Bernautas, 2003).

For oilseed rape, the price ratio increased from 3 to 4 between 2000 and 2008, and for winter wheat from 5 to 7. As seen from Figure 3.14a, for oilseed rape, typical current values for ERoN are 2–5 €/€ in Germany and the UK and 1–2 €/€ in Lithuania, where there is a low yield potential. At an ERoN below 1, it is not cost-effective to apply N to the crop. For winter wheat, ERoN ranges from 3–7 €/€ in Germany and the UK to 1–2 €/€ in Spain (Figure 3.14b).

Excluding non-production related issues, such as environmental considerations, the objective of farmers is to apply N at the economic optimum N rate. As also mentioned above, the maximum biological yield should not guide the decision about the fertilizer application rate, since associated ERoN values are substantially lower when targeting the maximum yield, and there is a risk that a farmer will lose money on the N-investment. Differences between actual N-rates and EONR, and between EONR and the N-rate for maximum yield amount to around 50 kg/ha, and at the present price level represent a value of about 40 €/ha. This is a marked proportion (8%–10%) of the total direct production costs for oilseed rape (400–600 €/ha) and wheat (300–500 €/ha) according to Zimmer (2008). Since it is often difficult for the farmer to estimate and actually match EONR for his individual fields, farmers tend to add N beyond EONR in order to secure high yields, which on the other hand can be harmful for the environment (see also Brink *et al.*, 2011, Chapter 22, this volume). This again emphasizes the importance in supporting farmers with improved and more accurate decision support systems for estimating EONR.

3.3.3 Nitrogen effects on quality of harvested products

The supply of nitrogen has a profound influence on the content of a large number of macro-molecules and secondary metabolites in plants which are important for their quality characteristics in relation to use for food, feed, fibre and bio-energy.

In particular, the relationship between N application rate and grain protein content in cereal crops has received considerable attention. High levels of N application result in increased grain protein content due to greater synthesis and accumulation of storage proteins. Particularly the content of gluten proteins, consisting of gliadins and glutenins, which together constitute more than 85% of the total protein content of wheat grains, is positively correlated with N-fertilization. Gluten proteins are the major determinant of the baking quality of wheat flour, affecting water absorption and mixing stability of the dough, its CO_2 retention capacity and the bread volume (Shewry, 2009). Increasing applications of nitrogen fertilizer to wheat result in an increased proportion of gliadin proteins and increased dough extensibility (Godfrey *et al.*, 2010). At the Broadbalk continuous winter wheat long-term experiment, the grain %N, protein composition and dough properties from plots receiving 35 t/ha farmyard manure per year, containing approximately 250 kg/ha of total N, was similar to that from the plot receiving 144 kg/ha per year N in inorganic fertilizer, indicating that much of the applied manure N was unavailable in the year of application (Godfrey *et al.*, 2010).

The minimum protein content required for bread making wheat is typically taken as 13% on a dry weight basis. However, farmers do often not get a substantial increase in payment for high-quality wheat with high protein content. Actually, the prices for baking quality wheat are in many cases not much higher than for feed quality wheat. In this connection it must also be emphasized that the quantity of protein is in itself not a sufficient parameter for characterization of wheat baking quality. Also the amino acid composition of the gluten proteins must be taken into account. The genetic constitution has a dominating influence on the composition of proteins and a large variability exists between different wheat genotypes. Thus, high quality wheat genotypes in general produce good bread wheat over a wide range of protein contents whereas poor bread wheat genotypes produce poor bread quality even if the protein contents are elevated by fertilization.

In terms of feed quality of cereals, high rates of N application may lead to a relative decline in the protein quality due to limitations in the amounts of essential amino acids. This is especially the case for lysine which is recognized as one of the most important essential amino acids because it is frequently the first limiting amino acid for optimal utilization of protein in monogastric animals and humans. Consequently, intensive research has been dedicated to increase the lysine concentration in cereals. It is evident that the lysine concentration of grain protein cannot be improved by fertilization which has stimulated plant breeders to focus on genotypes with a high lysine production. Several barley and maize genotypes have been developed in which the lysine concentration has increased by more than 50%, but abnormal phenotypes are usually developed in these lysine-rich genotypes, resulting in reduced yields (Shewry, 2009).

The ideal grain protein concentration of malting barley for production of European lager beer is 10.7% of dry matter, with a permitted range of 9.5%–11.5%. Higher protein levels result in lower starch content, less alcohol and risks of cloudy beer, whereas yeast activity may be limited by N shortage at lower grain protein levels (Pettersson and Eckersten, 2007). This optimization of N fertilization for production of malting barley is a delicate balance, because reduced N application decreases yields, but favours the desirable low protein content of the grains. In addition, grain size, grain weight, extract yield and wort viscosity, all positive quality parameters in malting barley, are reduced when the rate of N application is increased. Growing barley with excellent malting performance is also complicated by the fact that low rainfall and high temperatures favour protein synthesis and might lead to excessive protein contents even if the N-application is kept at a low level.

Important quality parameters for crops grown for bioenergy purposes are summarized by Karp and Shield (2008). There is limited knowledge on how increasing nitrogen supply affects the composition and proportions of ligno-cellulosic compounds in plant cell walls. Wheat straw consists of 35%–40% cellulose, 20%–30% hemi-cellulose and 20%–25% lignin (Mosier *et al*., 2005). N fertilization seems to cause a small decline in ligno-cellulose per unit straw dry matter (Porteaus *et al*., 2009), but the effect is not marked. This may be related to the fact that N stimulates the biosynthesis of phenylalanine and tyrosine which are precursors for lignin biosynthesis, thereby counteracting the general decline in C/N ratio in response to increased tissue N status. In poplar trees, N fertilization decreases wood density, cell wall thickness and lignin content (Pitre *et al*., 2007).

3.4 Trends in European N use in livestock production

3.4.1 Livestock productivity in EU-27 and feed resources

Since the Second World War, animal production in Europe has undergone a substantial increase. Expansion of fertilizer use and imported feedstuffs from outside of Europe has contributed to the increased production. Nowadays, the 27 Member States of the European Union are self-sufficient for milk and meat.

Characteristics of European livestock industry are shown in Table 3.4. First of all, Europe produces 26% of world milk production, achieving this from only 2% of the world's grasslands. High fertilizer use per hectare of grassland and high milk production levels per dairy cow in Europe are the responsible driving forces. Second, the EU production of pig and poultry meat and eggs totals 40 million ton, representing 16% of the global production of these products. Pigs and poultry are fed especially with crop products and so they rely on arable land. The EU share of global production for pig and poultry meat is double that of global arable land (17.9% vs. 8.6%, Table 3.4). This illustrates how substantial imports of protein rich oil cakes and meals from other parts of the world are responsible for the high level of European pig and poultry production.

European livestock consumed in total 473 million ton of feedstuffs in 2007 (Fefac, 2009). Roughages and cereals grown and consumed on farm of origin contributed 48% and 13%, respectively, to this feed base. Compound feed and other feed materials contributed the remaining 32% and 7%, respectively. One third of the consumed compound feed was imported, mainly consisting of oil cakes and meals, and feed cereals (Fefac, 2009).

3.4.2 N use in the diets of pigs and poultry

It has long been known that protein is an essential dietary component for all animals. Later, it was realized that it was not protein per se, but amino acids as the constituents of proteins that played the essential role (Lewis and Southern, 2001). This basic knowledge on the importance of amino acids in relation to productivity (growth and reproduction) has been central for improvements in nitrogen utilization efficiency (NUE) in monogastric animals for more than three decades. It was also recognized that some of the 20 different amino acids present in proteins were essential and have to be fed to the pigs and poultry, whereas some are non-essential and need not be provided in the diets because these amino acids are synthesized by the animals. Unfortunately, cereals and protein feedstuffs also contain an overload of non-essential amino acids in relation to the animals' requirements.

The factors affecting pig and poultry productivity and NUE are summarized in Table 3.5, providing an overview of the main issues to be addressed in order to improve NUE in pigs and poultry. Historically, the first approach in modern pig and poultry farming was to feed protein-sufficient diets to animals. This resulted in an improvement in the overall

Table 3.4 Global and EU-27 data for land use, animal numbers, and animal products for the year 2007

	Unit	World	EU-27	EU-27 share of world
Arable land	10^6 ha	1 411	121	8.6%
Grassland	"	3 378	69	2.0%
Cattle	10^6	1 361	90.3	6.6%
Dairy cows	"	245	24.3	9.9%
Pigs	"	921	161	17.5%
Poultry	"	17 887	1 341	7.5%
Dairy milk	10^6 ton	571	148	25.9%
Beef meat	"	62.3	8.2	13.2%
Pig meat	"	99.5	22.7	22.8%
Poultry meat	"	88.0	10.9	12.4%
Eggs	"	59.3	6.4	10.8%

Source: FAO (2009).

Table 3.5 Main factors affecting the productivity and nitrogen excretion and utilization in pigs and poultry

Factors	Methods	Productivity	N excretion	N utilization (NUE)
Dietary means	Protein balanced diets	Higher productivity	High	Low
	Balanced dietary amino acid supply	↔	↓	↑
	Substitution of protein with industrial amino acids[a]	↔	↓	↑
	Increasing bioavailability of amino acids	↔	↓	↑
Feeding strategy	According to physiological requirement	↔	↓	↑
	Use of increased number of diets	↔	↓	↑
	Optimization of feeding systems, e.g. avoid waste	↔	↓	↑
Breeding	Selection programmes	More efficient (kg gain / kg feed intake; litter size)	↓	↑
Management	Compilation of above mentioned methods/ tools	High productivity, welfare and product quality	↓	↑

[a] The effect depends on which essential amino acids are available on the feed market, but the number of industrial (crystalline) amino acids increases.

nutrient efficiency, as the productivity of the pigs was markedly increased and because the maintenance requirement for protein/amino acids was lowered due to the higher daily performance. Increased knowledge on the specific need for the different essential amino acids was followed by tools for balancing the dietary nutrient contents. Thus, practical diets for pigs and poultry were composed to fulfil the specific needs for amino acids by optimizing the use of the available feedstuffs.

The first limiting amino acid in cereals is lysine calling for the need for protein supplements from alternative sources such as soybean, rape seed, sunflower meal, etc. Industrially produced amino acids may also be used in crystalline form, but in this case it is also necessary to address the next limiting amino acids (normally methionine, threonine, tryptophan, isoleucine, valine, histidine and others). Nowadays, crystalline amino acids are widely used in order to reduce the overall protein content in diets for monogastric animals, but the exact use depends on economy and the demand for reduction in environmental emissions. Besides addressing the protein and amino acid content (profile) of feedstuffs, efficient N use requires that the amino acids are bio-available, because unavailable protein/amino acids will be excreted and not utilized. In summary,

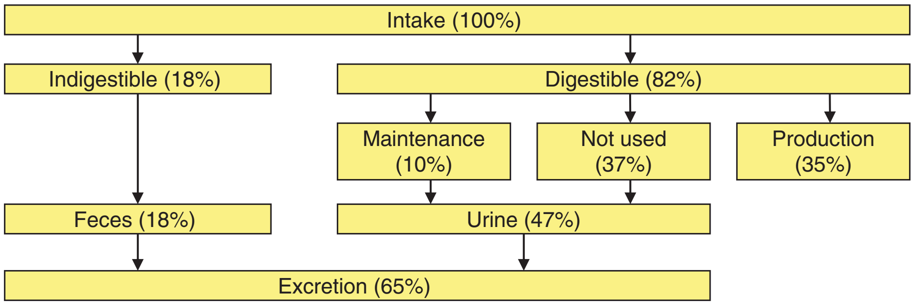

Figure 3.15 Scheme of nitrogen flow in growing-finishing pigs from 25 to 110 kg.

diet formulation needs information on amino acid content and availability in each single feedstuff in order to optimize a balanced diet for the animals according to their requirement. Most countries use feed evaluation systems and optimization programmes for balancing proper diets.

Lowering the proportion of feed with a low protein digestibility in the diet in favour of cereals and other feedstuffs with a higher protein digestibility will result in a better balance of dietary protein. A schematic representation of N flow in growing pigs is presented in Figure 3.15, which shows that only one-third of the N provided with the feed is retained in the growing pig. The proportion not used (37%) is mainly due to an imbalance in the amino acids provided.

A temporally varying feeding strategy is another tool used to improve NUE in pig and poultry production. In principle, each single animal should be fed exactly what it needs each single day. Although this is not possible in practice, it is now widespread to use more than one diet through the whole production period. This means that several diets are used sequentially for feeding a pig from weaning to slaughter. Two diets, viz. a starter diet and a weaner diet, may be used for the young pig and two or more diets for the growing pig. The nutrient content of each diet is adjusted to the physiological need for that period (Dourmad *et al.*, 1999). Phase feeding systems are also used in poultry production in order to fit the nutrient supply to the animals' requirement. Another – often forgotten – factor in order to improve NUE, is to minimize the loss of feed caused by inappropriate feeding equipments and feeding systems.

Finally, the effect of animal breeding should be considered. In modern animal husbandry, the animals have undergone genetic selection for productivity. This means that modern breeds demand less quantity of feed for producing one unit of product, implying an improvement in NUE. Animal management factors are also very important in order to ensure a high NUE. These include the use of efficient feeding equipment and systems, appropriate shifts in diets at different production stages as well as practices to ensure good hygiene and health status of the animals.

Improvements in NUE for pig and poultry farming have been achieved over the last two decades in many European countries. Denmark can be considered as one of the leading countries in this respect, reflecting environmental pressures to improve NUE and N excretion rates. As shown in Table 3.6, the N intake in Danish finisher pigs, covering the period from 30 kg body weight until slaughter, was gradually reduced by 30% from 1985 to 2009. At the same time, the N excretion decreased from 72 to 41 g per kg body weight gain. As a consequence, NUE has significantly increased from 28% to 42% by means of the tools mentioned in Table 3.5. These numbers demonstrate that feeding management, genetic breeding and diet composition are important tools to improve NUE. However, in the majority of European pig production systems, much still needs to be done to achieve this improvement in NUE (Jongbloed and Lenis, 1998). Corresponding results have been obtained in poultry, where genetic improvements have contributed to the improvements in NUE together with dietary changes.

As already discussed, feedstuffs not only vary in N, amino acid content and digestibility, but also in amino acid content expressed per kg N. For economic reasons, it is impossible to formulate diets without oversupplying certain amino acids, particularly when many by-products from the food-processing industry are used.

3.4.3 Dairy farming

Dairy farming systems combine animal production and grassland production. A useful way to analyse such systems is to consider NUE and the related input–output balance on a farm scale. At this scale, inputs of N_r to the farm include bought fertilizer and feedstuffs, while the outputs consist of sold milk and meat. Since animal manure is produced on the farm it does not figure directly in a farm input–output balance or in the calculation of overall NUE, although N losses are represented indirectly by reducing outputs.

There is an extensive literature on nutrient balances for dairy farming in European countries (see also Jarvis *et al.*, 2011, Chapter 10, this volume). The nutrient balance studies can be divided in to three groups:

(A) nutrient balances on farming systems (see below),
(B) nutrient balances on animal production (section 3.4.4),
(C) nutrient balances on grassland production (section 3.4.5).

Nutrient balances from group B and C facilitate the interpretation of the farm scale balances in group A.

A group of 20 intensive cattle farms in Portugal, with zero-grazing, had over a period of three years an average NUE for milk and meat of 33%. The intensive production on these farms was characterized by an average surplus of 502 kg N/ha (Fangueiro *et al.*, 2008). In principle, such intensive systems without grazing can achieve higher NUE, but suffer from very high N surpluses.

Table 3.6 The development in nitrogen intake, excretion and utilization in an average Danish finisher pig from 1985 to 2009. Calculations based on standard values according to Poulsen *et al.* (2006), which are updated annually (Poulsen, 2009). The values are given per kg gain for a finisher pig (30 kg to slaughtering). The body weight at slaughter has gradually increased from less than 100 (1985) to 107 kg (2009)

	1985	1990	1995	2000	2005	2009
Intake, kg N/animal	7.1	6.5	5.2	5.1	5.3	5.2
Excretion, kg N/animal	5.1	4.5	3.3	3.2	3.2	3.0
Excretion, g/kg gain in animal weight	72	65	47	45	44	41
Nitrogen Use Efficiency (NUE), % of N intake utilized	28	30	37	38	40	42

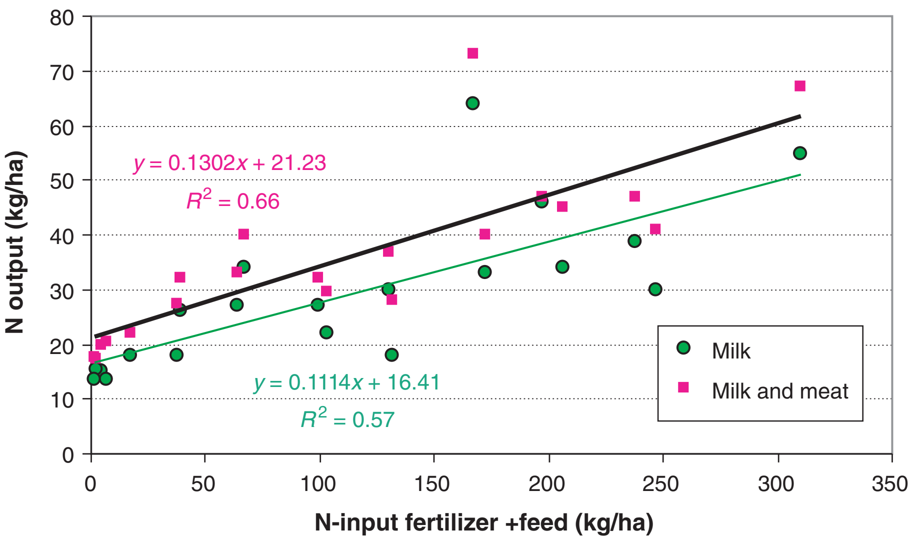

Figure 3.16 N use efficiency on European dairy farms expressed as annual N output in milk and meat per annual N input in fertilizer + feed. Slope of the curves indicates gross NUE (based on data from Bleken *et al.*, 2005).

By contrast, extensive cattle farms in Finland achieved, over a one year period, an almost similar average NUE for milk and meat of 25%, but a much smaller average surplus of 109 kg N/ha (Virtanen and Nousiainen, 2005). Finally, 21 intensive dairy farms in Ireland were studied during a period of four years. The first year, the average NUE for milk and meat was 18% and the surplus was 277 kg N/ha. Due to lower fertilizer application rates, the average NUE increased to 20% and the surplus decreased to 232 kg N/ha in the last three years (Treacy *et al.*, 2008). Bleken *et al.* (2005) reviewed a large number of European dairy efficiency studies and found a gross NUE of only 13% for the combination of milk and meat produced or 11% when only the milk was considered (Figure 3.16).

There are many options to improve the NUE on dairy farms. Feeding management addresses the crude protein content of the ration, for example by decreasing the N fertilizer application rate on grassland or by implementing fodder maize or other crops in the ration. Manure management involves minimizing ammonia losses during animal housing and manure storage, application of manure under favourable weather conditions during the crop growing season, and minimizing the contact time between manure and the atmosphere. Shortening of the grazing period also has a positive effect on the NUE due to the low N fertilizer value of excreta deposited in the meadow, although housing can increase the percentage loss of N as ammonia to the atmosphere (Webb *et al.*, 2005).

Intensification of production per animal means that less animals are needed for the same production level of milk at the farm scale. Feed intake on the farm scale can therefore be reduced and this leads to higher NUE and lower N surplus. Replacing grass with more on-farm grown fodder crops can lead to rations more balanced to the animal needs and this will improve NUE and lower the N surplus at farm level. Intensification of milk production at the farm level with external feedstuffs will also typically improve NUE, but it will, however, increase farm N surplus, and hence the risk of environmental losses. Furthermore, the environmental N losses occurring from the field production of the external feedstuffs are also not included in the balance (Kohn *et al.*, 1997; Schröder *et al.*, 2003; Bleken *et al.*, 2005).

3.4.4 Animal production and nitrogen use efficiency

From the previous section, it can be seen that there is potentially a tension between improving NUE and minimizing nitrogen surplus. In seeking to maximize the benefits of N, strategies are therefore desirable that benefit both indicators. In this way reduction of N excretion (and hence N surplus) may be associated with improved NUE.

Table 3.7 Nitrogen excretion and nitrogen use efficiency for Dutch livestock categories. Figures are converted to animals kept housed for 365 days per year. Data from CBS (2009)

	Nitrogen excretion (kg/year)		Nitrogen Use Efficiency (% of intake)	
	1990	2008	1990	2008
Ruminant animals				
Dairy: Regions with high fodder maize ration				
Female cattle for replacement < 1 year	40.1	34.9	14.3%	15.5%
Female cattle for replacement > 1 year	93.1	73.7	6.2%	6.6%
Dairy cows; lactating cows	141.7	127.6	19.4%	26.3%
Dairy: Regions with low fodder maize ration				
Female cattle for replacement < 1 year	44.3	39.5	13.1%	14.0%
Female cattle for replacement > 1 year	95.9	76.7	6.1%	6.4%
Dairy cows; lactating cows	157.0	144.2	17.8%	23.3%
Beef cattle:				
Veal calves on milk	10.6	10.7	51.2%	49.8%
Veal calves on fodder maize	30.8	27.4	28.9%	28.6%
Male beef cattle < 1 year	28.9	26.0	28.0%	30.7%
Male beef cattle > 1 year	72.6	53.8	10.9%	15.7%
Suckling cows	110.7	84.9	10.1%	11.4%
Sheep (including lambs)	25.0	14.4	9.3%	13.5%
Goats (including kids)	19.9	16.0	15.9%	25.2%
Horses		58.4		1.9%
Monogastric animals				
Fattening pigs	14.3	12.9	29.8%	35.6%
Sows (including piglets)	33.8	30.8	28.0%	36.8%
Broilers	0.61	0.53	41.0%	49.9%
Laying hens < 18 weeks	0.38	0.34	22.9%	26.9%
Ducks for meat	1.12	0.76	34.3%	49.3%
Turkeys	1.98	1.71	37.5%	44.8%

NUE is calculated as the ratio of nitrogen in milk and meat over nitrogen intake with roughage and concentrates. The milk production per cow for the two indicated years was 6050 and 7926 litres per year. The calculation method made use of country-wide average feed intake levels for all individual animal categories concerning concentrates, ensiled grass and fodder maize. For ruminants, the amount of consumed grass was assumed to close the energy demand of the animals.

Excretion rates can be calculated as part of an input–output balance approach on animal level, using the simple equation

$$\textit{Excretion} = \textit{feed intake} - \textit{animal products}.$$

Assessments of the N excretion rates and the corresponding N use efficiencies for the main animal categories in the Netherlands show that dairy cattle N excretion rates in regions with a high share of fodder maize in the ration are lower than those in regions with low share (Table 3.7). An increasing milk yield does not necessarily lead to increased N excretion rates, partly caused by decrease of the amount of applied fertilizer N in the same period, resulting in a lower protein content of the consumed grass. However, according to Witzke and Oenema (2007) comparing data from EU member states, there is a reasonably close positive relationship between milk yield and N excretion rates, with a standard variation across Europe of ±23%. It should be underlined that these N excretion rates are in fact the resultant of different animal rations with varying protein contents between the EU member states.

Ruminants generally have a lower NUE than pigs and poultry, as seen from Table 3.7. Finally, young animals have a higher NUE than older animals. Using the same principle for NUE, an intensive Italian survey was undertaken for estimating N excretion rates. Based on about 10 000 cows with an average milk yield of 8366 litre of milk per year, an average N excretion of 116 kg per year was found. Compared to the Netherlands, the Italian rations were mainly based on corn silage with lower feed N concentrations, thereby reducing N excretion (Xiccato *et al*., 2005).

Feeding trials with high yielding cows on a research farm of the Swedish University of Agricultural Sciences showed that varying the crude protein content of the ration between 135 and 184 g crude protein per kg feed resulted in NUE for milk production between 18% and 40%, with the lower protein content increasing NUE (Nadeau *et al*., 2007). Another approach is to use a model based on feed intake according to the energy requirements for maintenance, meat and milk production; this will enable improved optimization of NUE and, hence, lowering of N excretion rates (Vérité and Delaby, 2000; Peyraud and Delaby.

For an overview of N recovery efficiencies in EU-27, the USA and the Netherlands see supplementary material for Chapter 3. 2004; Dämmgen *et al*., 2009).

3.4.5 Economic value of N in dairy farming

To illustrate the economic value of N in livestock production, the case of dairy farming is used here as an example.

Grassland productivity and N response

Grassland productivity is affected by climatic factors such as rainfall and temperature and depends on the specific farm management. Nitrogen is one of the key factors to improve the productivity of grasslands, assuming no other nutrients are limiting. Soil N supply (SNS) is that originating from other sources than fertilizer. Recommendations for fertilization of grassland and arable land take the SNS into account, implying that the amount of inorganic fertilizer or animal manure can be lowered accordingly.

An analysis of Dutch nitrogen fertilizer experiments on grassland during the period 1934–1994 showed that increasing fertilizer applications resulted in higher N uptake by the grass, but at the same time the N use efficiency (NUE) decreased. The analysis also showed that grazing leads to a higher SNS and to a lower NUE, compared to cutting. These effects were stronger with pure grazing than with mixed grazing and cutting (Vellinga and André, 1999). For reasons of uneven distribution and high local N loadings with urine, N in the manure which is deposited directly in the meadow has a much lower mineral fertilizer equivalent (MFE) value than N in manure spread on the field provided appropriate abatement techniques of ammonia loss are implemented.

Today, the optimum N fertilization rate is based on economic and environmental targets. Until about 1990, the economic criterion was a marginal N response of 7.5 kg dry matter of herbage per kg N fertilizer applied. This criterion implied economically optimal fertilizer rates up to around 400 kg N/ha grassland (Prins, 1983) when harvested as cut sward. Much lower values (around 200 kg N/ha) are found for grazed grass swards (Deenen and Lantinga, 1993; Lantinga *et al*., 1999; Nevens and Reheul, 2003). Nowadays environmental targets are directed to lower protein contents of herbage and to meeting the Nitrate Directive, both leading to lower fertilization levels in the Netherlands (Vellinga *et al*., 2004; Oenema *et al*., 2011, Chapter 4 this volume).

Information on the geographical distribution and corresponding productivity of European grasslands has been published recently (Smit *et al*., 2008). The potential grass yield varies strongly between regions in Europe and reflects areas with different natural productivity levels (Peeters and Kopec, 1996; Smit *et al*., 2008). The potential production of herbage dry matter (DM) can be divided into three classes:

- 10–15 ton/ha: North-western Europe (Atlantic coastal area),
- 5–10 ton/ha: North and east Europe,
- 0–5 ton/ha: Southern Europe (semi-arid Mediterranean, not irrigated).

Grass yield trials in NW Europe (cut grass only) show annual DM yields up to about 16 ton/ha at N rates of 300–500 kg/ha (Figure 3.17). For cut grass, annual yields without N fertilizer application range between 2 and 6 ton/ha and the maximum yield between 8 and 18 ton/ha.

Effect on milk production

Based on datasets of 19 dairy farm groups (Bos *et al*., 2003; Raison *et al*., 2006; Bleken *et al*., 2005; Aarts *et al*., 2008) there is a fairly good correlation between the fertilizer N rate applied to fodder crops (mainly pasture) and the milk production (R^2 = 0.57, same dataset as in Figure 3.16). A survey of 139 dairy farms in the Atlantic area, ranging from Ireland to Portugal, shows a ratio of milk production per unit N applied to fodder crops ranging from about 29 kg milk per kg N on extensive farms with grazing to 547 on intensive farms without grazing (Raison *et al*., 2006). Data suggest that intensive farms are more efficient with fertilizer N (more milk per kg N applied) but this is also an effect of a higher proportion of feed concentrates and imported feedstuffs in total N-input. The N-losses for production of these concentrates or imported fodder are not accounted for in the farm balance, and hence the true NUE for the overall production of milk may be lower (see also Section 3.4.3).

Economic return on N for milk production

The economic return on N for milk production (ERoN; see also Section 3.3.2) were derived for grass yield response curves in the UK and in the Netherlands (Figure 3.18). The fertilizer N rate used in the calculations was that needed to obtain grass yields supporting a maximum annual milk production of 10.3 ton/ ha for the Dutch case and 5.9 ton/ha for the UK case. Because present-day intensive dairy farming uses considerable amounts of feed concentrates, a fixed annual value of 100 kg/ha N as feed concentrates was used, typical for intensive dairy farming.

ERoN values for price levels since 2000 (fertilizer:milk price ratio increased from 2 to 3 and is still rising, see Figure 3.13), range from 2–7 € per kg milk/€ per kg N when targeting maximum milk yields per ha, and exceed 15 €/€ at present N-fertilizer levels in the Netherlands and the UK. ERoN values tend to be higher than those for arable agriculture, because,

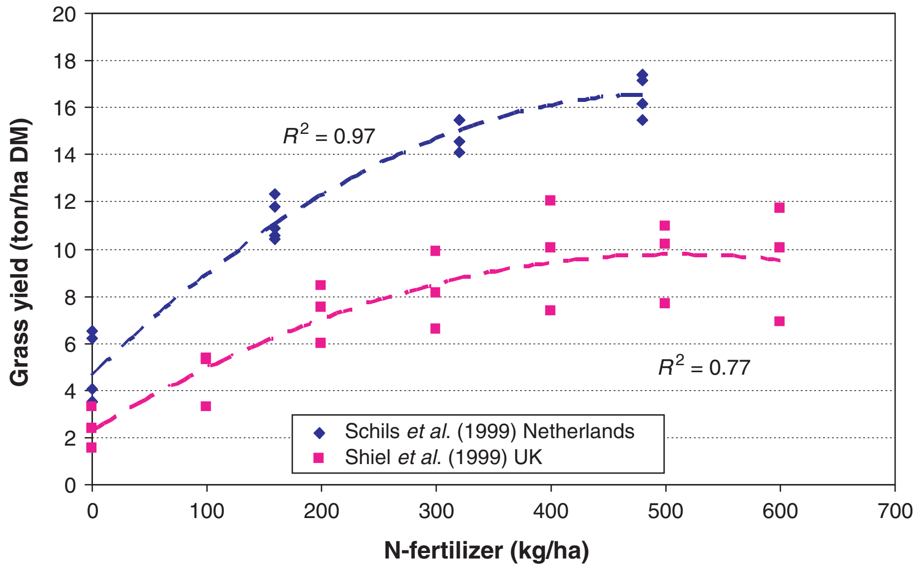

Figure 3.17 Examples of grass yield response curves for cut grass in response to annual N fertilizer inputs.

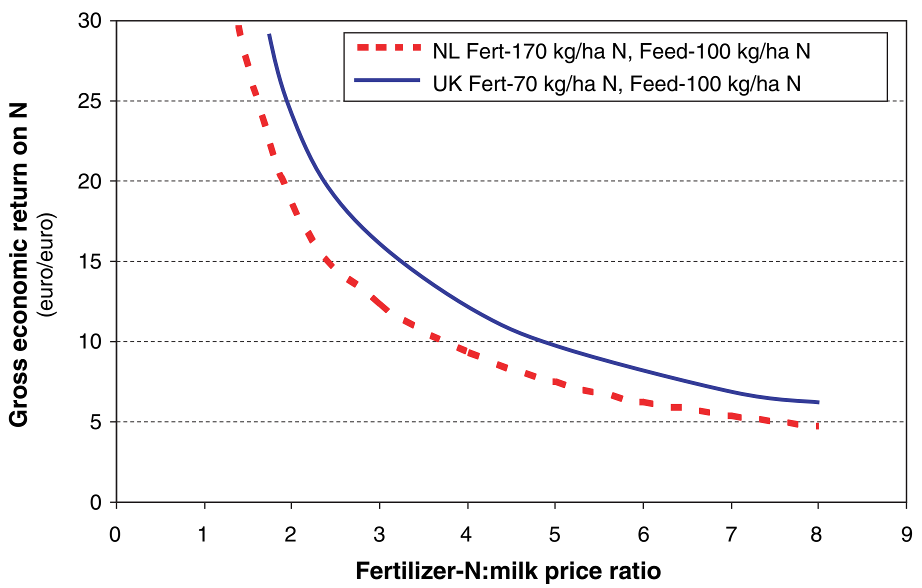

Figure 3.18 Gross economic return on nitrogen fertilizer (ERoN) application to grass for milk production as function of fertilizer N:milk price ratio (€/kg N per €/kg milk) for average fertilizer N rates (indicated in legend) and use of feed concentrates in the Netherlands and the UK. N response based on trials in the Netherlands and in the UK (see Figure 3.17).

in contrast to wheat and oilseed rape, grass yield continues to increase up to N-rates beyond 400 kg/ha.

The high ERoN for fertilizer N in milk production compared to crop production indicates how large the incentive is for the dairy farmers to apply large, and likely also excessive, amounts of fertilizer N for grasslands. Although farmers in south-eastern Europe generally use lower N fertilization rates than in north-western Europe, with significant possibilities for increasing their milk production level, the low ERoN under their production conditions (climate, soils, etc.) typically provides little incentive for them to increase fertilizer N use.

3.5 Industrial uses of dinitrogen gas and reactive nitrogen based compounds

Industrial uses of nitrogen cover a range of different applications. The gas dinitrogen is used to maintain for instance an inert atmosphere, while reactive nitrogen forms (especially ammonia and nitric acid) are used as ingredients in the chemical industry (rubbers, plastics including nylon, melamine), in the electronics industry for etching and pickling (nitric acid), in production of primary metals via leaching (nitric acid) and for cleaning catalysts used in for instance petroleum refining. In the food industry, ammonia is used for refrigeration of foods, and in the medical field it is used to refrigerate medical samples. Industrial dinitrogen gas uses worldwide are summarized in Table 3.8, while the following sections summarize they ways in which major reactive N compounds are used (Maxwell, 2004).

In Europe, industrial and other uses than fertilizers consume 23% of total European ammonia production (Table 3.9) but 35% of total European ammonia is exported, so industrial and other non-fertilizer uses of ammonia constitute roughly one third of the total ammonia consumption. From Table 3.9 it can also be seen that western Europe is a net importer of ammonia, the majority coming from eastern Europe and central Asia.

Table 3.8 Uses of industrial dinitrogen gas worldwide (Maxwell, 2004)

Application	Market share (%)
Chemical industry	33
Oil and gas extraction	14
Electronics	13
Primary metals	11
Petroleum refining	10
Food industry	5
Glass	2
Rubber and plastics	1
Miscellaneous	11

3.5.1 Ammonia

Ammonia is one of the best known bulk chemicals in the world, and the major synthetic nitrogen products made from ammonia are shown in Figure 3.19. Ammonia is predominantly used as feedstock for the production of fertilizers. It is produced by the Haber–Bosch process, invented by Fritz Haber in 1908, and turned into an industrial scale process by Carl Bosch in the years after. In the Haber–Bosch process, hydrogen from natural gas is combined catalytically with free nitrogen gas in the air at high temperature and pressure, yielding ammonia (Domene and Ayres, 2001).

According to Yara (2009), 83% of all ammonia produced globally was used for fertilizer production. Beside from the direct fertilizer use of ammonia, it can also be used as a reactant with respective acids to produce ammonium nitrate, ammonium phosphate and ammonium sulphate. Reacting liquid ammonia with carbon dioxide at about 190 °C and elevated pressure according to the so-called Basaroff reactions yields the fertilizer urea (Maxwell, 2004).

The remainder of the ammonia is used in various other processes. The most important compound made using ammonia as a reactant is nitric acid. In three steps, ammonia is converted to nitric acid based on the so-called Ostwald process, using precious metals as catalysts at elevated pressure and temperature (Buchel *et al.*, 2000). Nitric acid in turn is predominantly used to make explosives, like ammonium nitrate, nitroglycerine, trinitrotoluene and nitrocellulose.

Ammonia is further used in the production of the cyclic amide caprolactam, a feedstock for the production of nylon-6, amines, polyacrylonitrile, hydrazine, polyurethanes, resins based on phenol or melamine, formaldehyde, nitriles, sodium nitrate, sodium cyanide and many others.

Nitrogen compounds are particularly used in technologies for cleaning flue gases after fossil fuel combustion. This includes the reduction of nitrogen oxides using ammonia, both catalytically as well as non-catalytically (Caton and Xia, 2004; Wojciechowska and Lomnicki, 1999; Baukal, 2003). Ammonia is also used for the removal of sulphur dioxide, although the technology is rather new and as such it is not widely used. With this technique, an electron beam passes through the flue gas and ammonia reacts with sulphur dioxide to yield ammonium sulphate (Chmielewski *et al.*, 2002).

Despite its toxicity, ammonia is regaining its position as a refrigerant due to the environmental concerns associated with chlorofluorocarbons. It has favourable thermodynamic properties, especially a low boiling point and high heat of evaporation, and is widely available for low prices (Redwood, 2010; Stoecker, 1998).

In the metal industry, ammonia is used for the extraction of metals such as copper, gold and tungsten from their respective ores (Wohler, 2009). In the extraction process, the metal ores are suspended in an ammonia solution and subsequently heated, thereby creating the corresponding metal-amines, which can be isolated. Ammonia can also be used for annealing/nitriding of steel (Ross, 1988) and as a corrosion inhibitor after conversion to quaternary ammonium compounds (Sastri, 1998).

3.5.2 Ammonium nitrate

Ammonium nitrate is predominantly used as a fertilizer and as an ingredient for explosives and propellants. In the United States, industrial explosives (including ammonium nitrate) account for approximately 4% of total reactive nitrogen output (Domene and Ayres, 2001). The major N containing explosives apart from ammonium nitrate are TNT, PETN, Tetryl, Nitroguanidine and Nitroglycerin. The principal non-military use of explosives is in coal mining, followed by quarrying, surface mining and construction work. All of the nitrogen contained in explosives is released directly into the atmosphere the moment they are used, mainly as free dinitrogen, but in the case of ammonium nitrate the majority is released as NO. Detonation of nitroglycerin also releases a significant proportion as N_2O, as much as 97 kg per ton of nitroglycerin, according to theoretical model calculations (Domene and Ayres, 2001).

Ammonium nitrate mixed with a suitable fuel, mostly fuel oil and as such abbreviated as ANFO, is a well known blasting agent used in the mining industry and for construction purposes, in which it has largely replaced dynamite (Persson *et al.*, 1993; Tatiya, 2005; Monroe and Hall, 2006). It is used in a 95:5 weight ratio of prilled ammonium nitrate to fuel oil. Another well known mixture is AMMONAL, which consists of 60 wt% ammonium nitrate, 20 wt% trinitrotoluene (TNT) and 20 wt% aluminium. Unfortunately, owing to the large scale availability of both ingredients of ANFO, the mixture has also been used for the construction of so-called improvised explosive devices (Turkington, 2009).

3.5.3 Urea

Urea is predominantly used as a fertilizer, since it has the highest nitrogen content of all known solid nitrogenous fertilizers (Schepers and Raun, 2008). Combined with formaldehyde, it forms a resin that is used in adhesives and plastics in general (called urea formaldehyde resins). The production of the bulk chemical melamine, a feedstock for predominantly plastics, is based on the ring closure of three urea molecules at elevated temperatures. On a smaller scale, urea is used as an ammonia source for removal of nitrogen oxides in flue gases, as an

Table 3.9 European potential nitrogen supply and demand balances in 2008 (FAO, 2008)

	Europe, total		Central Europe		Western Europe		Eastern Europe + Central Asia	
	(million ton N and % of supply)							
NH_3 max. prod. capacity (as N)	37.5		6.2		10.3		21.0	
NH_3 actual prod. (as N)	33.6	100%	4.8	100%	9.7	100%	19.0	100%
N fertilizer consumption	14.4	43%	2.7	55%	8.6	88%	3.1	17%
Non-fertilizer N demand & others	7.7	23%	0.6	13%	5.2	54%	1.9	10%
Balance (+: export, −: import)	+11.5	+34%	1.5	+32%	−4.1	−42%	+14.0	+74%

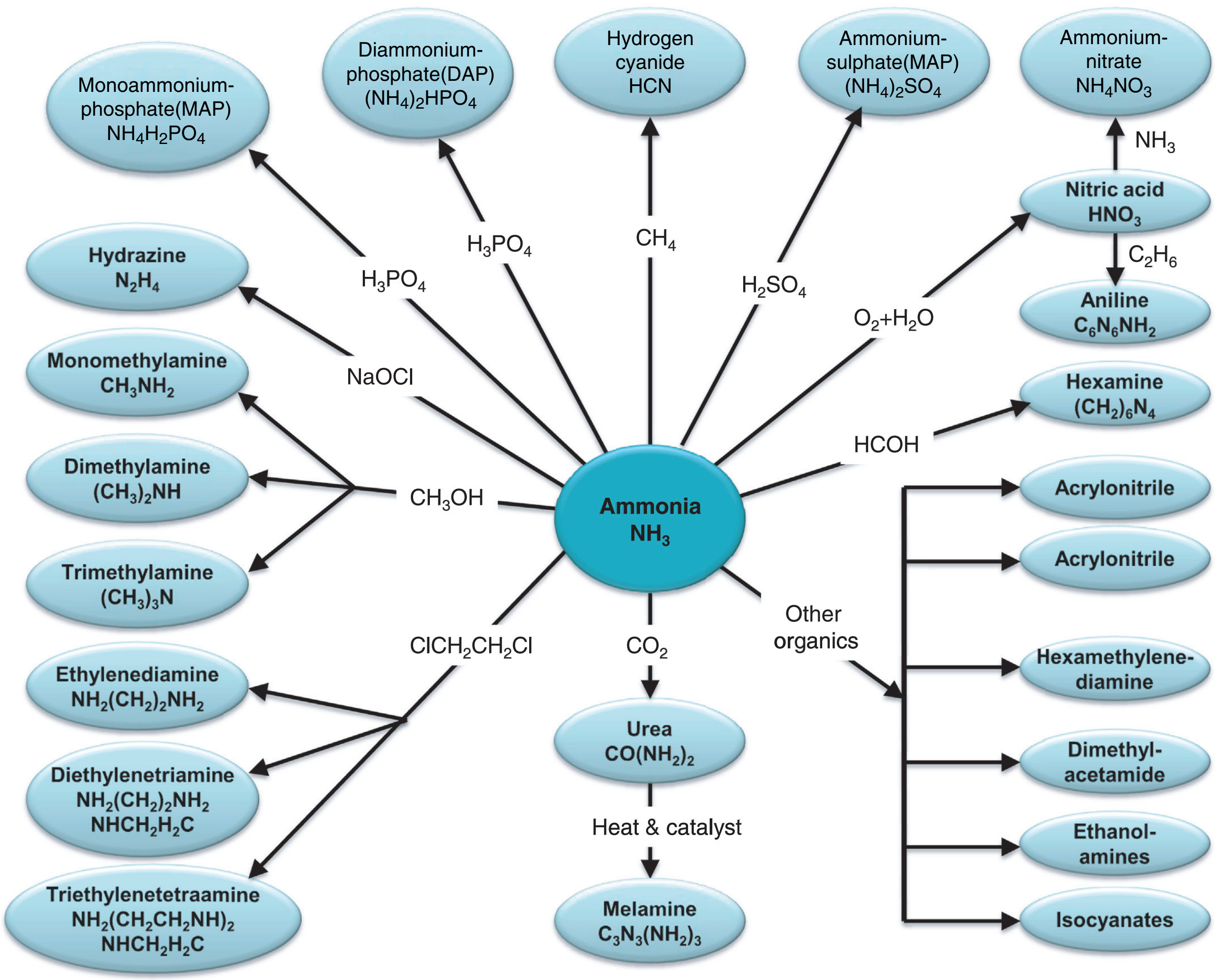

Fig. 3.19 Synthetic nitrogen products made from ammonia (modified from Maxwell, 2004).

intermediate product in the pharmaceutical industry, as well as a reactant for the production of urea nitrate.

3.6 Economic value of reactive N use to the European economy

There are various ways to approach the economic value of reactive N. Taking a global perspective, Erisman *et al*. (2008) argued that nearly 50% of the world human population in 2008 could be fed thanks to Haber–Bosch derived N_r applied as fertilizer. The global revenue on sale of fertilizers in 2005 amounted to nearly 30 billion USD (25 billion €; Yara, 2009).

For the EU-27 countries it was estimated by Yara (2009) that the increase of wheat production in 2008 due to use of mineral N fertilizer was 64 million tons. This estimation is based on a comparison with the wheat yields achieved in ecological farming without mineral N fertilizer. The fertilizer-derived increase in wheat production represents a net economic gain (grain value minus fertilizer costs) of 7.6 billion € per year for the entire EU, or 280 €/ha. However, this net gain is sensitive to the relatively volatile world market prices for grain and fertilizer, as seen during the 2008–9 food crisis and subsequent financial breakdown, and assumptions on the potential yields in absence of mineral N fertilizer.

At the level of a farm or a crop, the cost of N fertilizer is just one of several production factors. As described in previous sections, the economic return on investment in N (ERoN) is a very robust measure of importance for the farm economy and, hence, for the farmer decisions. Judging from Figures 3.14 and 3.18, the following current ERoN values can be summarized.

The farmer will make a profit from N inputs if ERoN is above

Product	**ERoN (€ product / € fertilizer N)**
Winter Wheat:	2–7
Oilseed Rape:	1–5
Milk:	10–15

one and the range in ERoN depends on (i) actual N fertilization level and (ii) shape of the response curve. A lower maximum yield for oilseed rape, wheat and grasslands is commonly found in south-eastern compared to north-western Europe. This is due especially to water limitation and implies a tendency for ERoN to be relatively low in south-eastern Europe compared to north-western Europe, where climatic conditions favour higher potential yields under economically optimal fertilizer N input. The ERoN ranges presented in this chapter mean that for most farmers there is a huge economic profit from use of N_r, especially in relation to livestock production. The high ERoN for fertilizer N in milk production compared to crop production indicates how large the incentive is for the dairy farmers to apply large, and likely also excessive, amounts of fertilizer N for grasslands.

In addition to chemical fertilizer, manure and biological nitrogen fixation are other sources of N that can be affected by farm management. The economy of N at the farm level is therefore quite complex. Costs of purchasing and handling of various N sources are quite different and change in time, e.g. depending on the price of energy (natural gas) and environmental policies (see Oenema *et al*., 2011, Chapter 4, this volume).

Compiling a comprehensive, robust inventory of the economic benefits to society of reactive nitrogen is not a simple matter. As indicated above, a coarse estimate may be that about half the value of European agricultural production may be considered as dependent on N_r supply. However, in a review of yield differences between organic and conventional farming in Europe, Offermann and Nieberg (2000) found that organic cereal yields are typically 60%–70% of those under conventional management, vegetable yields are often just as high as under conventional management and pasture and grassland yields in the range of 70%–100% of conventional yields. The derived consequences for economic profit or benefit are quite complicated as Offermann and Nieberg (2000) also state that the majority of the studies evaluated report an increase of labour needs, on average in the range of 10%–20% (but higher for vegetables), the cost of which has to be accounted for. Therefore the economic benefits of N_r use in agriculture are not easy to estimate.

In the case of industry, the overall economic value includes nearly all explosives (including the economic value of military security; Erisman *et al*., 2008), the value of coal and other products mined with explosives, and the wide diversity of other nitrogen-containing chemical compounds. For industrial uses, however, i.e. especially explosives and plastics, there are alternatives for using N_r, and therefore the real value of N_r becomes very difficult to assess.

For agricultural production, there is no simple substitute to N_r at the scale of its current level of use, but also the N_r contribution to agriculture is challengeable (Bruges, 2007). Although we have estimated that between 30%–50% of the current food production, population and GDP may be derived from use of N_r, to some extent N_r has also replaced labour. Historically, human development has been driven by the big transition in which labour force for agriculture was transferred to industry and services. The continued productivity in agriculture was ensured partly with fossil energy for machinery and N_r, partly with modern pest control agents and breeding for improved crop genotypes.

Another issue is that economic benefits in the modern definition include the externalities, i.e. the negative effects (or benefits) of N_r for which there is no market. This issue is discussed at length in Chapter 22 of this volume (Brink *et al*., 2011).

The real societal price of food is that including the external costs, or alternatively formulated, is the price of food produced without any external effects. Including externalities of N_r use (and of P, pesticides, fossil fuels, etc.) in the price may then enable transfer of part of the labour back to food production to maintain food production at lower external inputs. However, this approach would not be easily applicable in a market based economy.

Given the many uncertainties in the assessment of the economic value of reactive N use to the European economy, the coarse estimate at the beginning of Section 3.6 may be as valid as any estimate derived from more refined calculations. Based on this and the additional data and arguments presented in this chapter it can be concluded that the overall benefits of N use are very substantial.

3.7 Perspectives and recommendations

The need to maintain food and energy security under an increasing world population poses major challenges to supply the quantity and quality of commodities (including biofuels), given the few options to increase arable land area. With its resource of relatively fertile and productive soils, Europe has a clear capability for contributing to this, and it may be argued that Europe also has a moral obligation to do so. However, increased land use changes elsewhere in the world may not exclusively be due to an eventually diminishing agricultural production in Europe if inputs of reactive nitrogen are significantly reduced, but these possible secondary effects of reducing European fertilizer N rates must be taken into account. At the same time, environmental concerns, including agricultural responses to climatic change, as well as the need to feed the growing global population, represent a major challenge for further improvement of nitrogen benefits, i.e. to increase the use efficiency of the reactive nitrogen applied.

The following recommendations for policy decisions and research priorities can be made.

- Initiatives, whether voluntary or legislative, to reduce the use or surplus of nitrogen in agriculture, including inorganic fertilizer N, should take account of the need to maintain the nitrogen benefits in agricultural production – food, feed and biomass productivity should be maintained while improving N use efficiency.
- Modified field management practices for N conservation, modifications to livestock diets and recycling of wastes can enhance benefits per unit N_r used, and should be strongly promoted as best available technology (BAT).
- New developments, combined with stimulatory incentives for farmers, should promote innovative technological tools to improve resource-efficiency and the overall benefits of N use:
  - (i) management strategies involving N-conserving field practices (e.g. catch crops, reduced soil tillage, better timing of N inputs, etc.),
  - (ii) modifications to livestock diets for decreasing N excretion rates,
  - (iii) enhanced manure N use efficiency through improved environmental technologies for management, recycling and field application of manures,
  - (iv) improved accounting of field level N responses depending on cropping practices, soil fertility and climate.
- New research initiatives should focus on:
  - (i) breeding plant species and crop varieties with improved nitrogen use efficiency through increased root length density at depth, high capacity for N accumulation in the stem, high maximum N-uptake rate and N remobilization during grain-filling,
  - (ii) improved composition of major feed crops and novel feed additives, e.g. proteins from bio-fuel production waste and other means of increasing feed N responses per unit mass N_r used,
  - (iii) new technologies for improving fertilizer application and sensing of crop N demand, including tools for improved utilization of N in agricultural and urban waste materials to increase overall N use efficiency.

3.8 Conclusions

- Although considerable uncertainty exists in the assessment of overall benefits of reactive nitrogen, particularly as regards the economic value of N_r in industrial production, it can be concluded that N_r is very much a key factor for achievement of food security and social welfare in Europe.
- Maintaining food and energy security under an increasing world population poses major challenges to supply the quantity and quality of commodities (food, feed, fibre and fuels). Changing the input of reactive nitrogen significantly to European agriculture may influence conversion of natural land areas to cropped land elsewhere in the world.
- Future legislative actions to reduce the use or surpluses of nitrogen in agriculture should take account of the need to maintain benefits for food security and farm economy in Europe.
- There is still a large potential for increased nitrogen efficiency in European agriculture by better management strategies, improved recirculation of nitrogen in waste materials, adoption of new fertilizer technologies, crop monitoring tools and new crop cultivars, all demanding improved skills of the individual farmers and their advisory service.
- The economically optimal N application rate for crops varies significantly across field, farms and regions, depending on crop type, crop N response, farm type, soil type and climate.
- Crop N use efficiency can be increased by improving prediction of the economically optimal N rate, but at the current relatively low ratio between nitrogen fertilizer costs and crop prices, farmers often have relatively little economic incentive to restrict N application, so long as environmental effects are considered as externalities.
- Nitrogen use efficiency for livestock production can be greatly improved, especially with optimized feed protein and amino acid composition, but also by animal breeding. Although intensification of livestock production with external feedstuff may increase N use efficiency, it should be noted that this may lead to larger local surplus of N (and other nutrients), necessitating application of environmental technologies for waste and manure processing to avoid increased environmental load.
- For dairy farming, nitrogen use efficiency can be improved by adjusting the nitrogen content of the feed to the requirements of the cattle and by minimizing the ammonia losses from animal housing and during manure application.

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Supplementary materials

Supplementary materials (as referenced in the chapter) are available online through both Cambridge University Press: www.cambridge.org/ena and the Nitrogen in Europe website: www.nine-esf.org/ena.

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