Chapter

10 Nitrogen flows in farming systems across Europe

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Executive summary

Nature of the issue

- Farms represent operational units which determine N-use efficiency and incorporation into products and, collectively, at the wider scale, determine the extent of environmental losses from agriculture.
- The basic principles and objectives of using N, from whatever source, pertain to different systems across the wide range of farming types across Europe.
- In addition to managing external inputs (fertilisers), there is much opportunity to improve N transfers within the farm. Mineral fertilisers are added to balance supply/demand for crops. Some systems rely on legume-N which, once incorporated into farm cycles, behaves in the same way as other N forms.

Approaches

- Farm N cycles, their constituent parts and controlling influences are described and generalised principles identified.
- Farm budgets for a range of systems, focussing on typical practice in NW Europe are shown which illustrate some general, important differences between farming systems.

Key findings/state of knowledge

- Benefits of using N effectively are far reaching with immediate impact in promoting production. Use of N also provides an effective and flexible management tool for farmers.
- Crop N requirements are determined from response curves and economic optima. Advice is supplied to farmers from various sources but the extent to which it is taken depends on many factors. New technologies are available to improve N-use efficiency. The basis of good N management is to optimise efficiency of added and soil N by increasing the temporal and spatial coincidence between availability and uptake of N.
- Current management drivers often cause farms to be 'open' with N losses. By changing focus from productivity-only to balances between productivity, product quality and environmental impact, managements can be redesigned to increase N use efficiency.
- Livestock farming presents particular problems with large potential N losses. Previously, animal manure was considered as a waste product rather than a nutrient source.
- Farm-based budgets are a simple way of representing gross flows of N into and from farms and provide important insights into N behaviour. Illustrative budgets show important differences between typical farming systems including conventional arable and livestock (pig, beef and diary) and organic dairy systems in NW Europe in their emissions and the ratio of emissions per unit of N in products.

Major uncertainties/challenges

- Nitrogen is mobile and potentially leaky: it is readily available for farmers to use (at cost) and easy to apply to crops, but requires skilled management.
- Technologies to improve efficiency are available, but need continued revision: farmer knowledge about the requirements for N use from both production and environmental perspectives is increasing, but there is much opportunity to extend this. A major challenge of modern agriculture has been to change perceptions about manure and to demonstrate the value and more efficient use of N from this source.

The European Nitrogen Assessment, ed. Mark A. Sutton, Clare M. Howard, Jan Willem Erisman, Gilles Billen, Albert Bleeker, Peringe Grennfelt, Hans van Grinsven and Bruna Grizzetti. Published by Cambridge University Press.

Recommendations

- Continued development of farm-scale models (including simple cycles and budgets) is required for policy but also for farm practice. Improved knowledge of farm budgets, including those from other farm types and regions is required. Continued programmes of providing advice to farmers are required so that new, available technologies are taken up.
- Research programmes are required to ensure a sound base on which to develop alternative managements and options to meet future economic and environmental (viz. climate change) challenges.

10.1 Background

Until about the middle of the twentieth century, the main N input to European farms was via fixation by legumes. This N was made available to non-leguminous crops after the decomposition of plant residues and by the recycling of animal manure. Thereafter, there was a period of 30–40 years during which the importance of manure-N to the farmer was greatly diminished, because of the availability of cheap and reliable synthetic N fertilisers and the increased demand for N created by agronomic practices that increased potential yield. This led to a tendency for manure to be considered as a waste product of animal husbandry, rather than a valuable source of nutrients. Over the past 20 years, the role of manure nitrogen has regained some of its former status and the use of synthetic N fertilisers has been decreasing. There have been three main forces driving this latest development: the increasing price of synthetic N fertilisers, the introduction of nutrient management legislation (e.g., the EU Nitrates Directive) and a greater awareness amongst farmers and consumers of the nutrient value of manures.

Farms represent the operational units at which decisions are made, which have impact on the efficiency of N use and incorporation into products, and collectively at the wider scale, determine the extent of transmissions of excess N into waters or the atmosphere. There is an enormous range across Europe in the ways that farms operate; this is dependent upon the type of production, farm location, soil type, climate and individual farm operational decisions amongst other determining factors. Nevertheless, the basic principles and objectives of using N, from whatever source, pertain to all of these different systems and are shown diagrammatically in Figure 10.1. The decision-making processes that determine N use are complex and highly interactive with both internal and external factors playing a role. This chapter attempts to describe some of the important factors which determine the flows and use of N at the farm scale.

The losses of N from natural ecosystems tend to be small, either because the supply of nutrients from natural sources, such as that through biological fixation, is relatively small and/or because labile forms of N are rapidly captured by the plants present. The purpose of farming is to produce food and fibre, and this is achieved by increasing both the inputs of nutrients and their mobility within the plant/soil ecosystem. Losses of nutrients from agricultural ecosystems will therefore nearly always exceed those from natural ecosystems. However, the extent to which food and fibre production (and income) is 'traded-off' against environmental pollution is much determined by the skill of farmers, and their aims and objectives, as these are influenced by many factors (Figure 10.1) in

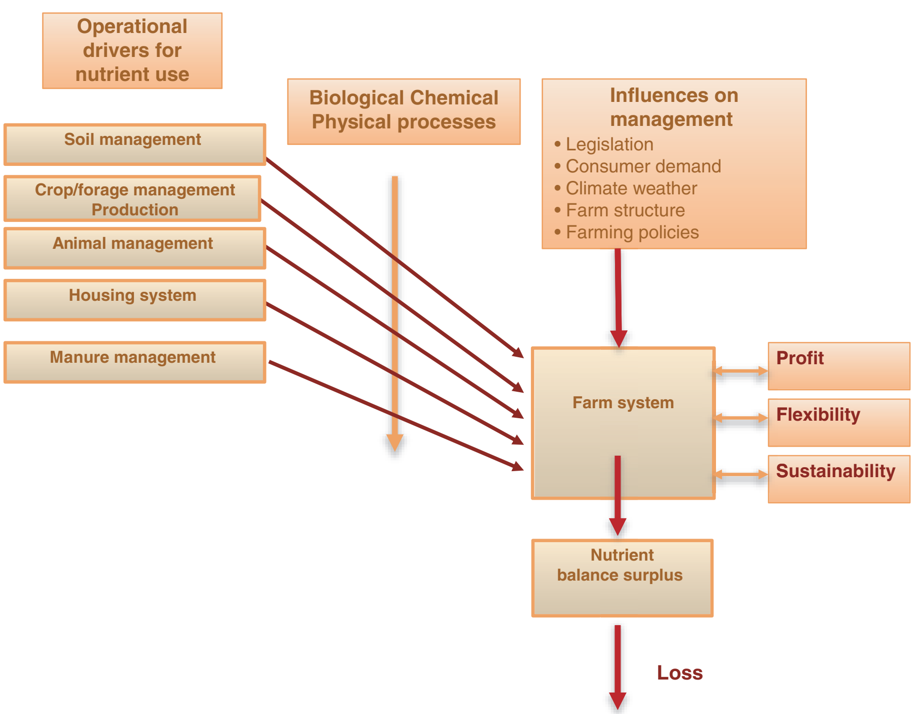

Figure 10.1 Influences and controls over N flows at the farm scale.

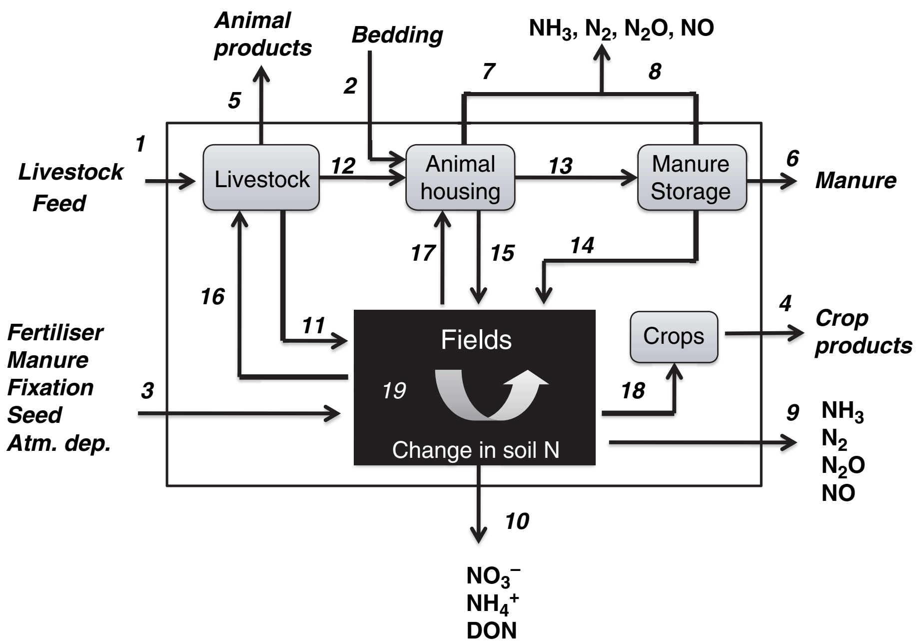

Figure 10.2 Schematic diagram of annual nitrogen flows on a farm. Atm. dep. = deposition from the atmosphere, DON = dissolved organic nitrogen. The numbers refer to the flow or transformation processes described in the text.

controlling nutrients on their farms. However, some loss is inevitable because many forms of N are, or have potential to be, very mobile and the farm is an open system which operates with some unpredictable factors such as rainfall. The farm-scale N cycle therefore controls the availability of excess N and contributes to a lesser or greater degree to effects at the larger, landscape or catchment scales within which it is a constituent part. The farm is therefore an important and convenient scale at which to consider effects and impacts, and is the operational scale at which any necessary controls to reduce flows of N to the wider environment are applied practically.

The totality of N flows for a farm system is shown in Figure 10.2 in which the numbers refer to the flows or transformations described in the following text. In many situations, there is an import of N from outside livestock farms both in imported animals and imported animal feed (1) and bedding (2). For both livestock and tilled cropping systems, N can be added to the fields from outside the farm in imported manure, mineral fertiliser, and seed and from the atmosphere via atmospheric deposition or nitrogen fixation in legumes (3). There is an export from the farm of crop products such as cereals and straw (4). Nitrogen is also exported from the farm in animal products such as livestock sold or milk (5). Some manure may be exported from the farm (6). The other N removals from the farm are losses as gases to the atmosphere from the components of livestock production (7, 8) and cropped or grazed fields as NH_3, N_2, N_2O or NO (9), or in run-off or leaching as NO_3^-, NH_4^+ or dissolved organic N (DON) (10). There may also be direct losses of these forms from animal houses, yards and manure storage areas.

The farm N cycle also involves much internal transfer and transformation. Thus in livestock systems, N not incorporated into animal protein or into milk is excreted in dung and urine either on the fields during grazing (11) or in animal housing, animal holding areas and feedlots (12). From there, it is either applied directly to land or enters the manure management system (13, 14, 15). The other important internal N transfers are the uptake into the crop either to be consumed directly by livestock (16, 17) or into tillage-crop production (18). There are also many internal transfers and transformations in the soil (19) which result in either sequestration into relatively immobile forms or release and transformation into forms that are either available for uptake by plants or further transfer into losses. That which remains in the soil is therefore the net effect of additions made to the soil, and a balance of the net effects of mineralisation, immobilisation, nitrification, denitrification, ammonia volatilisation and plant uptake.

The concept of a farm N cycle is inter-connected with that of budgets: the system shown in Figure 10.2 can, if all the various components can be quantified, be used to provide a systems balance or budget. The detail that a systems balance provides is most relevant to those involved in research and in developing complex models of the N flows. For more practical purposes, soil, livestock and farm gate balances are those which are used. The soil balance represents the net effect of inputs and removals from a specified area, usually a field, and thus enables a prediction of the potential supply of N for future crops and is used for estimating additional supplies required from fertiliser inputs. Both the soil and livestock balances can be used for calculating the N use efficiency of these components, as well as the need for nutrient inputs. The 'farm gate' balance is a simplification of the full system balance and simply calculates external inputs from all the sources (flows 1+2+3 in Figure 10.2) and the removal in products (flows 4+5+6 in Figure 10.2). From this information, the surplus or deficiency in the farm system can be determined. This surplus has been used to demonstrate the efficiency of N use in the system and any potential for leakage to the wider environment, i.e. an indicator of pollution potential.

The flows of N within a farm scale are controlled by the same processes and transformations as discussed elsewhere (de Vries *et al.*, 2011, Chapter 15, this volume), but the local, intense concentration of various forms at particular stages of the cycle, means that the equilibrium at these points is pushed towards a faster rate of cycling resulting in a greater probability of loss than in natural ecosystems. This effect is at least in part dependent on the efficiency of utilisation of N in the various components of any farming system (see elsewhere and later in this chapter). However, the livestock component, whether integrated into mixed systems or operating as a separate enterprise, has major effects on environmental consequences. This is largely because their excretal products will almost entirely be returned to land either on the same or another enterprise. The major immediate environmental impact is through NH_3 volatilisation and, N_2O and NO volatilisation, either directly from urine patches in the field, from excreta in sheds, yards and hard standings, from stored solid and liquid manures, or from their application to land. The NH_3 emitted can be deposited back to land either within the same holding or after being transported (sometimes many hundreds of kilometres) away from the farm unit. If the farmer treats the manure as a waste rather than resource, there is a danger that the crops will be over-supplied with N, leading to increases in NO_3^- leaching. If urea fertilisers are used there will also be volatilisation especially when applied to the surface of the soil without rapid incorporation, in grasslands for example. This may also occur with NH_4^+-based fertilisers in alkaline soils.

10.2 Controlling on-farm N supplies

10.2.1 On-farm sources

In addition to relying on external inputs from fertilisers etc., there is much opportunity to use the N that is transferred between various internal sources. Some farming systems utilise, and organic systems rely on, N input from legumes, which is acquired through biological fixation. This fixed N, once it has become part of the crop, whether it be grain or forage, then enters the farm cycle in exactly the same way as other forms of N entering the farm. Because this input is usually relatively small, especially when compared with intensive managements with large levels of fertiliser, the losses from legume based systems are often viewed as being smaller than those from fertiliser-based managements. However, this comparison needs to be made on a like-for-like basis when the whole system is considered: where N inputs of fertiliser and from legume are similar, then losses are also comparable (Hutchings and Kristensen, 1995). Grazed monoculture white clover achieved losses as NO_3^- and NH_3 which were comparable with those from a sward receiving 400 kg N/ha/year (Jarvis *et al.*, 1989). However, there is no direct loss, as may sometimes occur when fertilisers are applied and, other than a biological cost to the plant, there are no other costs associated with biologically-fixed N production. Nitrogen fixed in this way is, however, more difficult to control and manage compared with fertiliser N when trying to target N supplies for cropping.

The role of the animal and its inefficiency have already been noted. The N contained within manures and slurries is an important resource. However, the composition of these materials is notoriously variable; the N that they contain is there partially in mobile forms, mostly as NH_4^+ ions, but large proportions are also present in organic forms. The amount of the NH_4^+ lost as NH_3 can be very variable and the rate of decomposition of organic N to plant-available mineral N is also difficult to determine. This makes it much more difficult to use than fertiliser-N in supplying N at the required rates and times to growing crops. The reliability and cheapness of fertiliser-N combined with the growing need to fill the gap between crop needs and other available supplies has led to an enormous increase in its use over recent decades, sometimes completely replacing animal manure, which once was the main fertilizer resource available to farmers. Nevertheless, the realisation that manure-N is an important resource has recently grown again, and farmers have increasingly incorporated a consideration of supplies from this source into their nutrient planning. Some farms have remained almost totally reliant on manures to supply the N requirements of their cropping systems.

The other important on-farm N resource is that contained within the soils. With the exception of legumes, crops are dependent upon N present in the mineral N pools as NO_3^- and /or NH_4^+ ions. The other major pool within the soil is the organic pool, in fact comprising a number of smaller pools containing materials of different ages and each with a different potential to supply N. Nitrogen can be added (immobilised) to, or be released (mineralised) from, these organic pools: this depends upon the action of the soil microbial biomass and the resistance of the organic matter to microbial attack. Supplies from soil organic matter are therefore very dependent upon the local environmental conditions (water and temperature especially), the soil texture and the nature of the organic materials that have been added (plant residues, manures and other organic supplements) in the recent or long-term past. Again, supplies are difficult to predict other than in general terms and it is therefore much more difficult to provide an effective index system to define the supply capability for N than it is for P and K: this may be even more difficult when manures have been applied over an extended period. However, supply from the soil is very important and, if the contribution it makes is not understood, then it cannot effectively be incorporated in nutrient planning. This introduces a further degree of inefficiency.

10.2.2 Balanced N fertiliser supplies

One of the keys to successful crop growing is the supply of the correct amounts of nutrients at the correct time in relation to peaks and troughs of crop growth. Where this cannot be achieved, there can, on the one hand, be a deficit of N in relation to demand, and on the other, a surplus. Where the former occurs, growth potential is restricted and when the latter occurs there is potential for loss. Because of the issues noted above, it is more difficult to achieve the correct balance of N supply from all sources than for the other major nutrients. To do so effectively for N requires knowledge of the supplies from all sources to be able to capitalise on these. In the past, in many circumstances and whilst fertiliser prices were relatively cheap in relation to the gain required, many farmers tended to use more rather than less N than may actually be required. However, perspectives have changed and N use efficiency has improved for many reasons.

Crop requirements have, in the main, been determined on the basis of response curves and a defined economic optimum, the point at which the returns in yield/income per unit of fertiliser applied are considered not to be viable. The response curve follows the principle of diminishing returns at this stage. Advice is supplied to farmers by independent advisors, government agencies and through various interactions with other farmers. The extent to which advice is followed depends upon the background (social, educational, peer influence) of the particular farmer, the cost and the income foreseen, and the way that current economic, legislative and other pressures influencing decision making (Figure 10.1). The way that advice is used or is supplied varies greatly from region to region, but is usually available as specific fertiliser recommendations, Codes of Good Agricultural Practice, in booklets or as computer based systems.

As well as straightforward N effects, there are many interactions with other factors which influence the efficiency of N use. Thus a shortage of water will restrict growth and hence uptake, as will a shortage of other nutrients. In the latter case, Liebig's Law of the minimum will be followed and use of the non-limiting nutrients through growth will be dependent on the availability of the limiting nutrient. Thus a sulphur shortage has been shown to reduce N uptake by grass swards and creates a surplus of N in the soil, enhancing the potential for its loss (Brown *et al.*, 2000), and conversely, as shown in Figure 10.3, N application has enhanced the use of potassium and phosphorus.

10.2.3 The role of the farmer

The importance of individual farmer decisions has been noted: much depends upon the skill and precision with which farmers decide on the acceptable level of risk associated with each their operations to determine nutrient application/management regimes. Farmers have multiple roles: they are custodians of important resources, the farm and the soils on which it resides, and they are managers and risk takers. And their skills determine the level of risk they are prepared to take to achieve financial gain and/or environmental benefit. However, the majority of farmers are businessmen and women, and many are entrepreneurs, whose primary aim is to optimise their production system to the benefit of themselves and perhaps of society as well. Further improvement of efficiency of N use within farming systems is dependent on the effective uptake of new knowledge and approaches as they become available from new research.

Figure 10.4 shows the difference between what was technically achievable and that being achieved by the best Dutch farmers in 2000. In all components of the system shown, there was a significant shortfall between what was technically possible and that achieved in practice. A similar examination of farmers with

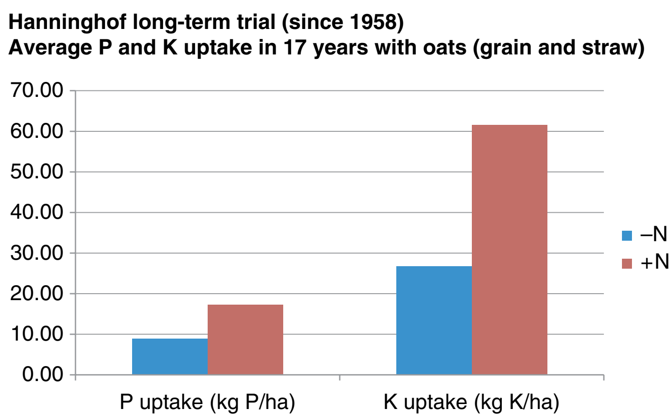

Figure 10.3. Effects of nitrogen application on phosphorus and potassium uptake (kg/ha) (F. Brentrup, personal communication).

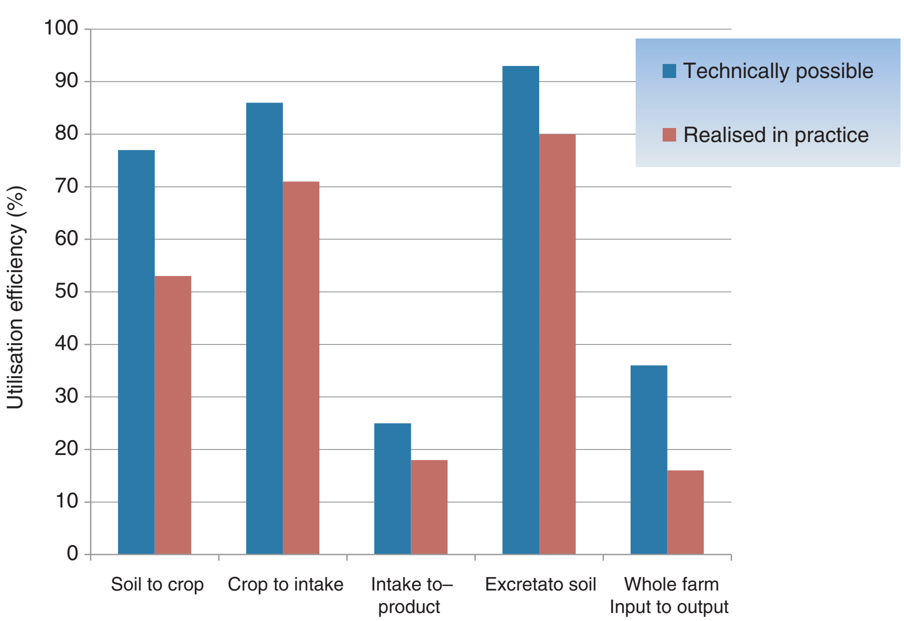

Figure 10.4 Potential for change for increased N efficiency (%) and that achieved in practice by skilled farmers (from Jarvis and Aarts, 2000).

less skill than those indicated in Figure 10.4 would show much larger discrepancies. Future research will extend the technically achievable efficiency of use. Skilled farmers will keep up with this and create the need to ensure that other farmers also increase their efficiency of N use.

10.3 Mechanisms affecting N use and loss in farming systems

The fundamental doctrine of N management is to optimise efficiency of both introduced and native soil N by increasing the temporal and spatial coincidence (synchronisation and 'synlocation') between availability and root uptake of mineral N (Christensen, 2004; Crews and Peoples, 2005). The management needed to assure the vitality of highly productive crops most often causes agro-ecosystems to be relatively 'open' with respect to losses. By moving the focus from productivity-only drivers to a balance between yield, product quality and environmental impact, farm management and associated agro-ecosystems can be re-designed to increase N use efficiency. Important management measures to improve N efficiency on farms include improved feeding efficiency of animals, reducing NH_3 losses and improving N retention in the crop–soil system as well as timing, rate, source/material and method of supply. The latter implies crop sequences that incorporate cover (or catch) crops, judicious use of soil tillage, improved timing and use of animal manures, crop residues and mineral fertilisers and a suitable balance between the plant production potential and animal stocking density.

Livestock production systems (in particular ruminants) have a considerably lower N use efficiency than those based on cash crops. When plant biomass is utilised by the livestock, up to 80–90% of the plant N is recycled on the farm. The handling and subsequent use of this N will unavoidably lead to losses with all the entailing environmental impacts already described. The main challenge for N management in farming systems is tightening the cycle, in particular those of livestock production systems. The total amount of N excreted by livestock in the EU-27 peaked at about 11 Tg in the late 1980s, which was very similar to the 12 Tg used as fertiliser (Oenema *et al.*, 2007). This illustrates the importance of considering both fertiliser and manure N inputs as well as the inputs from biological N fixation.

10.3.1 Nitrogen turnover in agricultural soils

In the soil, N undergoes a variety of largely microbial mediated transformations, which are associated with organic matter (OM) turnover. Agricultural soils contain a large pool of organically bound N: Figure 10.5 shows an expanded view of the soil compartment shown earlier in Figure 10.2. The soil layers exploited by plant roots typically contain 5000–15 000 kg N/ha.

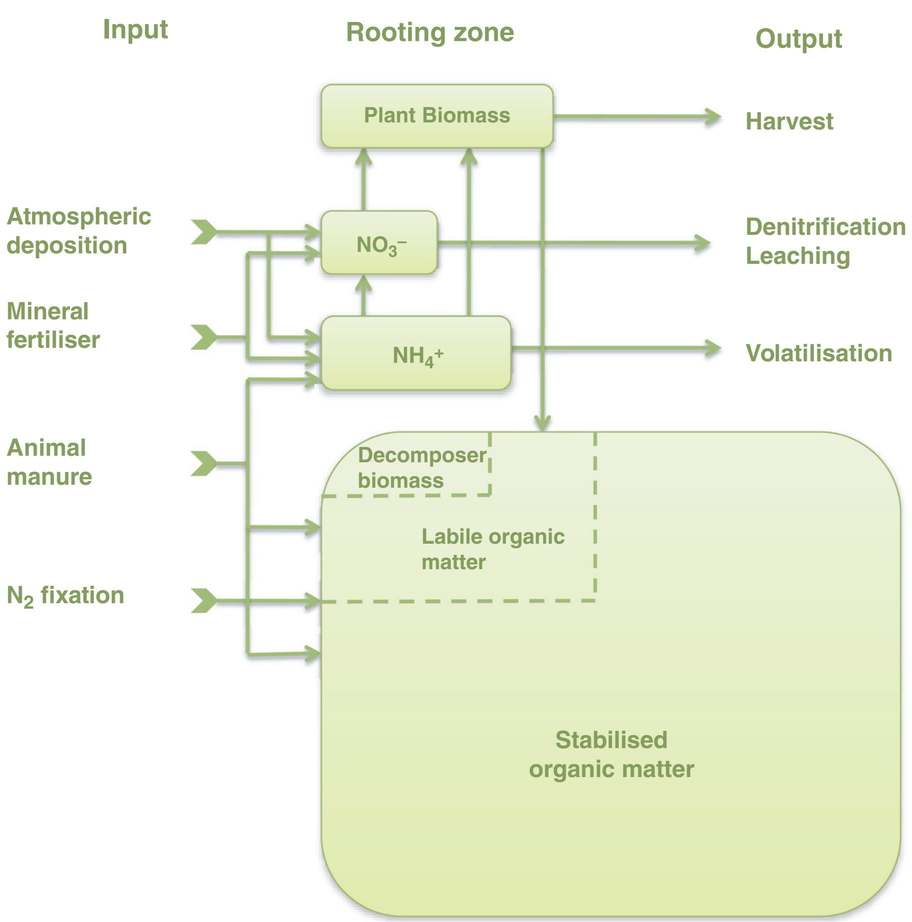

Figure 10.5 The nitrogen flows in a typical arable soil showing major inputs, outputs and pools of nitrogen (from Christensen, 2004).

However, only 1%–2% of this large pool may in any given year become available to crop uptake within the growing period. The pools of N that dominate the short-term N cycle are the decomposer-biomass and labile OM pools. These N pools are relatively dynamic and respond readily to inputs of plant residues and animal manure, changes in moisture and temperature and to soil disturbances, as caused for example by tillage.

Nitrogen occurs in the soil in chemical forms with widely different characteristics in terms of availability to plants and susceptibility to losses. Ammonia located at the soil surface can easily be lost by volatilisation, particularly at alkaline pH (Sommer *et al.*, 2003). NO_3^- is very mobile in the soil solution and thus susceptible to leaching, whereas NH_4^+ is retained in the soil through sorption to soil colloids or fixation in clay minerals. Nitrification and, in the main, denitrification are the sources of gaseous losses as NO, N_2O and N_2. By far the largest fraction of organically bound N is retained in the soil, but under some circumstances soluble organic N losses may be significant (Murphy *et al.*, 2000).

Through the mineralisation–immobilisation turnover processes, mineral N becomes available from soil organic matter (SOM) for plant uptake, but also for losses to the environment. The rate and the seasonal and spatial distribution of these processes influence the composition and productivity of the vegetation. Natural ecosystems (including many grasslands) exhibit a large degree of synchrony and synlocation between release and uptake potentials and losses are generally small. In contrast, most arable cropping systems are relatively open, primarily because annual crops with a large N demand during the vegetative growth phase are used. Management also introduces massive physical disturbance of the soil structure through tillage and affects hydrology through drainage and irrigation. Management of these systems therefore causes the dynamics of the processes to differ substantially from those of natural ecosystems, in particular by reducing the synlocation and synchrony in the N turnover and a reduced return of organic matter to the soil, which collectively reduce N-use efficiency.

10.3.2 Mineral fertiliser

The use of mineral fertiliser as one source of plant nutrients is an essential component of current agricultural practice. Mineral fertilisers are applied in order to balance the gap between the nutrients required for economically optimal crop development and the nutrients supplied by the soil and by available organic sources. This gap results from a permanent export of nutrients from the field with the agricultural products. Today, the N gap is closed by an annual application of 97 Mt mineral fertiliser N at the global scale in 2006 (IFA, 2006). Mineral fertiliser N should, in principle, be applied at the time and location that is optimal for crop uptake and thus lead to potentially high N-use efficiencies. However, in practice many factors may reduce the actual efficiency obtained and although some farmers are more effective than others, this is one of the areas where there is still potential to make improvements (Figure 10.4). There are many ways to define and measure N use efficiency. Here, we will apply two different approaches: (i) the apparent recovery efficiency (RE_A), which is the increase in N yield (or total biomass) divided by the amount of N applied and (ii) the direct recovery efficiency (RE_D), which is the amount of labelled N that is taken up in a crop (usually only in above-ground material) following application of addition of ^{15}N labelled fertiliser.

The RE_D of mineral fertiliser N applied in autumn has been measured at 11–42%. For spring-time applications this increases to 42–78%, illustrating the effect of improved timing of the application for improving synchrony with crop uptake (Christensen, 2004). Typical RE_A values in research plots are *c.* 40–50% for small-grain cereals, when defined on grain N yield, and this is increased to 60–70% when based on total above-ground N uptake (Balasubramanian *et al.*, 2004; Olesen *et al.*, 2009). The RE_D values are generally smaller than RE_A values because some of the applied N is incorporated into microbial biomass and possibly into SOM. Experiments with ^{15}N-labelled fertilisers applied to wheat have shown larger RE_D values in humid than in dry environments, illustrating the importance of environment for N-use efficiency. However, the retention of residual ^{15}N in the soil increased with increasing dryness. Post-harvest NO_3^- losses of residual fertiliser N is usually less than 5%, indicating that NO_3^- that is susceptible to leaching during autumn and winter in humid environments mainly originates from mineralisation of organic N. Fertiliser applications should be calculated to provide the smallest rate necessary to obtain the optimum crop yield achievable at the specific site, and to ensure the quality of the crop. European farmers usually meet the needs of the crop by using several separate N applications to prevent deficiency in periods of peak demand as well as to ensure no over-supply. Properly applied N application allows farmers to manage the development of the crop and to influence yield by the promotion or indirect inhibition of individual yield components, and directly improve yield quality. Such fertiliser strategies are widely used to contribute to the yield and quality management of cereals, which occupy more than 50% of EU arable land.

Response curves and farmer choice of optimal rates

When increasing amounts of N are applied to different plots on the same field, in the same year, and on the same crop, the yields obtained from the plots usually form a typical response curve (Figure 10.6). The economic optimum for the farmer is usually defined as when the cost of the last unit of N applied is still covered by the value of the additional yield it produces. Establishing the correct fertiliser rate for a crop is a complex process, which involves many different factors such as crop type, expected yield and quality, nutrients available in the soil and changes in available nutrients during the growth period. In many countries, soil analysis is used to estimate the mineral N content in the rooting zone at the start of plant growth in spring to improve the decision for the first application. However, during the following growing season, the available N will be subject to the conversion processes noted elsewhere and which vary both in space and time. Furthermore, the need of the growing crop is also influenced by favourable or unfavourable growing conditions (Figure 10.7). As a result, the economic optimum fertiliser rate for a specific crop changes from

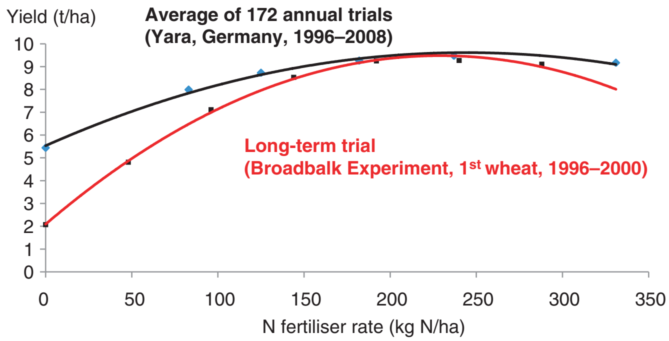

Figure 10.6 Average yield response to increasing annual N application rates in winter wheat (172 annual field trials in Germany, 1996–2008) and yield response in a long-term field trial with winter wheat (Broadbalk Experiment, average yields 1996–2000) (F.Brentrup, personal communication).

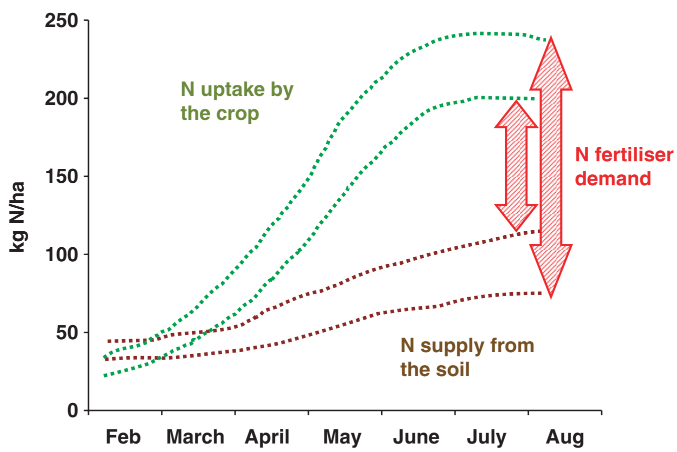

Figure 10.7 The amount of nitrogen taken up by a crop depends on the growing conditions of the particular field and varies according to the growing conditions of the year (between the green lines). Mineralisation also varies from year to year (between the red lines). Therefore, the 'correct' application rate for the same crop in the same field (red arrows) will differ from year to year and may need adjustment during the growing season (F. Brentrup, personal communication).

year to year and from field to field and, for N, methods based only on soil analysis to determine that available for the crop have limited reliability and can serve to estimate rates needed at the start of growth, but require supporting decisions during the season.

Split application strategies based on the N status of the plant can assist growers to adjust the available supply several times during the growth period. In this way the problem of a varying demand in different fields and in different years can be better managed. Thus, during the past 20 years, scientists and farmers have focused on methods based on direct plant analysis in the field to determine the optimum rate. Different methods have been developed for practical use (such as the NO_3^- sap test and, making, chlorophyll meter) to assist the decision.

The above-mentioned methods are based on representative samples and thus provide a single average recommendation for the field, which makes them appropriate for smaller fields. Soil properties, nutrient availability, crop growth and final yield can vary widely within single fields (Figure 10.8). As a consequence, optimum fertiliser rates also vary and since the early 1990s, variable rate technology has been developed to improve efficiency of inputs and lead to economic and environmental benefits. This technology, or more generally 'Precision Agriculture', aims to manage crop variability by tailoring inputs to specific needs in any particular part of the field. Variable application of N is of particular interest because N has the largest immediate effect on crop growth, yield and quality. The most promising systems for measuring within-field variation in crop growth are based on imaging crops by remote sensing and spectral indices derived from the reflectance spectra have been shown to be indirectly related to their N status. Using this information, spatially variable fertiliser application plans can be made to meet the optimum in each part of the field, which can be illustrated as a 'map'. Experiments and practical experience indicate several potential economic and environmental benefits, including increased N efficiency, more uniform crop stands, ripening, and quality, easier harvesting and greater yields.

10.3.3 Manure handling and N use efficiencies

For at least one millennium, manure of livestock fed on semi-natural grassland or with legume fodder crops was the only available fertiliser resource for croplands. During the last part of the 20th century, the abundance of manufactured fertiliser with predictable yield effects caused farmers to consider animal manure as a waste product of animal husbandry rather than a valuable nutrient source. One of the main challenges of modern agriculture has been to change this perception and to document and demonstrate a more efficient use of this N. Some 70–80% of livestock excreta are collected in housing systems in EU-27, with a tendency for this to increase (Oenema *et al.*, 2007). The remaining 30–20% of livestock excreta is dropped at grazing, where it is difficult to manage but contributes to the N economy of the system. More than half the manure collected in housing systems is managed in the form of slurry or liquid, while the remainder is managed in a solid form and often includes larger quantities of bedding material (e.g., deep litter or farm-yard manure). There is a huge regional variation in manure management systems in Europe (Menzi, 2002). Slurry-based systems are dominant in the Netherlands and Denmark (>90%), while separate collection of slurries and solids dominate in UK, France and Central/Eastern Europe (<50% slurry/liquid). Most of the slurries are stored in tanks with or without covers, but some is stored in unsealed pits in Central Europe. The EU Nitrates Directive obliges Member States to properly store (for up to nine months) and manage manure. However, in practice, implementation in some countries has been slow.

There are many loss pathways for N after excretion in the animal house, manure storage or after application in the field. However, the dominant loss is through NH_3 volatilisation. The urea in the excreted urine is rapidly hydrolysed to NH_3 which can be volatilised, especially if it is placed on open surfaces, if pH is alkaline and if temperatures are high (Sommer *et al.*, 2006). Modelling studies indicate that in 2000 almost 30% of the N excreted in animal housing systems in EU-27 was lost during storage; approximately 19% via NH_3 emissions, 7% via nitrification and denitrification (NO, N_2O and N_2) and 4% via

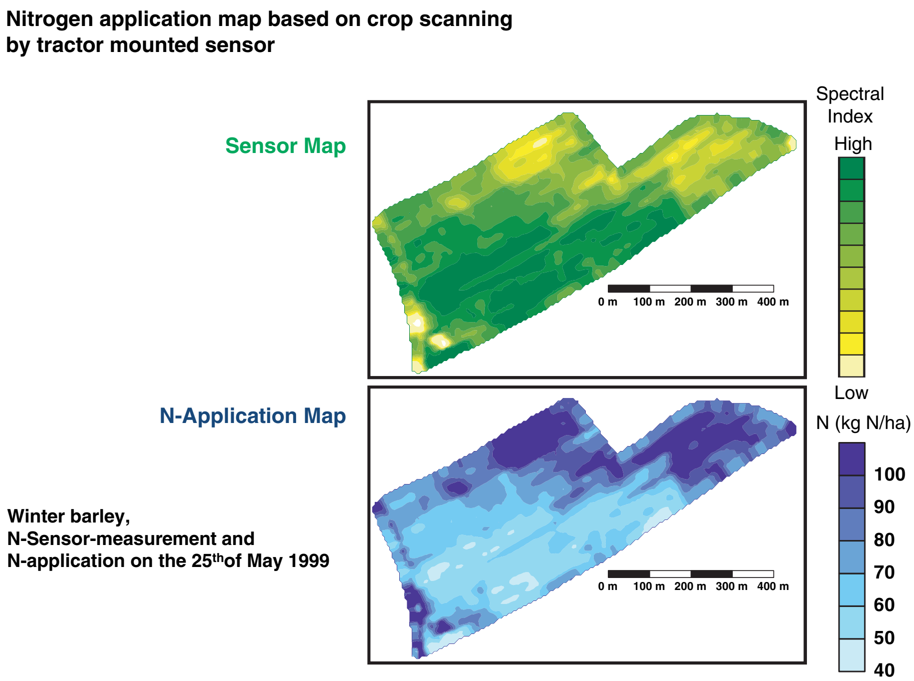

Figure 10.8 Nitrogen application 'map' based on crop scanning by a tractor-mounted N-Sensor™ (winter barley, 25 May 1999, F. Brentrup, personal communication).

N leaching and runoff (Oenema *et al.*, 2007). Another 17% of the N excreted in the housing was lost via NH_3 volatilisation following application. Thus in total, 48% of the N excreted in animal housing was lost during storage and immediately after application. Because of the significance of this, we pay special attention to this loss route.

Ammonia emission from animal production

During the last decades much research on NH_3 emission reduction has focused on constructional measures for animal houses and on low emission application techniques for manures. The guiding principle is minimising the contact surface and contact time between animal manure and the surrounding air. Examples are decreasing the evaporating area of the manure in the storage pit and frequently removing the manure to an outside storage and using sod injection for slurries on grassland and direct ploughing after land spreading on arable land (Starmans and Van der Hoek, 2007). Measures with respect to animal feeding have effects on excretion and on NH_3 emission. Dutch research on cattle feeding showed a linear relationship between milk urea content and the emissions from housing. An increase in the milk urea concentration from 20 to 40 mg/100 gram milk resulted in increasing emissions from 5 to 9 kg NH_3 per cow in a cubicle cow during the 190-day winter season (Van Duinkerken *et al.*, 2005). The resulting decrease of the NH_4-N content of the manure will, however, reduce volatilisation losses during manure storage and manure application. Dutch research on pig feeding showed reductions in emissions of up to 70% as a combined effect of reducing the N content of the feed, additives affecting the pH of the manure and resulting in a change of N in urine into faecal protein (Aarnink and Verstegen, 2007).

Emission from solid poultry manure is governed by manure characteristics such as pH, temperature and water content. Microbial breakdown of uric acid and undigested proteins into NH_3 is dependent on moisture content. The positive effect of drying poultry manure on lowering emissions was demonstrated in pilot studies and on practical farms (Groot Koerkamp, 1994; Groot Koerkamp *et al.*, 1998; Starmans and Van der Hoek, 2007).

Slurry injection into bare soil and trailing hose application and injection (Nyord *et al.*, 2008) to growing arable crops (Sommer *et al.*, 1997) reduce NH_3 emissions substantially. Sod injection on grassland or ploughing directly after manure spreading on arable land is very effective in reducing emissions (Huijsmans *et al.*, 2001; 2003). In theory, choosing the right meteorological conditions for spreading can help to reduce emissions from land spreading of manure. However, farmers may have limited choice about the timing of manure applications, because of operational constraints such as availability of contractors or regulatory considerations (such as those imposed by the restrictions of the Nitrates Directive). The efficacy of this approach has yet to be proved in practice.

Improving N use efficiency from manures

Many different technologies for reducing housing and storage emissions and improving manure quality have been tested and are increasingly being implemented. These include reducing fouled surface areas in animal houses, covering manure stores, acidification of slurry to reduce pH, slurry separation, biogas digestion, incineration of solid manures, etc. Some of these treatments not only reduce N losses but may have other advantages such as providing energy or increasing the total fertiliser value of the manure.

Fewer measures are available for reducing gaseous N losses from solid manures than for slurry, partly because much of the scientific research and technical development has been in areas of Europe where slurry is the dominant form and because NH_3 losses from slurry are much greater than from solid manures. Significant losses of NH_3 can occur from stored solid manure, if there is composting or self-heating (Sommer, 2001; Dämmgen and Hutchings, 2008). When implementing measures to reduce N emissions from the manure management system, it is important to take a whole system approach. Reducing NH_3 emissions from animal housing may result in greater emissions from subsequent stages storage, field application unless additional measures are taken (Hutchings *et al.*, 1996). For animal manure to be a reliable source of plant-available N, NH_3 losses need to be small, and the distribution across the field should be as uniform as for mineral fertiliser. This often requires use of expensive equipment supplemented with measurements of NH_4^+-N in the manure just before application to precisely target crop needs.

Crop recovery of N in manure varies widely. Compared with the 42–78% RE_D values cited above for mineral fertilisers, the RE_D values for manure applied in spring is only 18–31% for faeces, while it is 61–88% for urine and poultry excreta (Christensen, 2004). The recovery of N in manure in the second year is comparatively small with RE_D values of 2–6%, and is almost independent of source of N. Storage facilities must allow manure to be kept over winter without significant loss of N. Application in spring is a prerequisite for maximising the N use from this source.

10.3.4 Crop residues (and rhizodeposition)

Crop residues returned to the soil represent a significant input, not only of N, but also of easily decomposable carbon, to the microbial decomposers in the soil. Application of residues with a wide C:N ratio (e.g., straw) can therefore lead to immobilisation of soil mineral N. Application of manure and plant material (as in a green manure crop) with a smaller C:N ratio will lead to more rapid decomposition and release of mineral N. Mature crop residues applied in autumn typically result in RE_D values of 8–13% and a grass incorporated in spring one of 70% (Christensen, 2004). Crop residues from legume crops provide an important source of N in many farming systems (in particular in organic farming). Studies using labelled N have typically shown RE_D values of 10–30% for N incorporated in legume N residues, which is considerably less than for fertiliser N (Crews and Peoples, 2005). These values are, however, misleading since a considerably larger proportion of the legume N is incorporated into the soil microbial N pool, and some of the microbial N is released as a consequence. In many cases, almost equally good RE_A values have been found for N in fresh legume residues as compared with that in mineral fertilisers.

Rhizodeposition of N during plant growth, which is the release of labile organic N into the soil from plant roots and from the nodules of legumes, may be an important source of N, and could represent from 25% to 43% of total N recovered in the crop (Russell and Fillery, 1996). Mayer *et al.* (2003) clearly indicate that N rhizodeposition of grain legumes (beans, peas and lupins) represents a significant contribution to the balance and N dynamics in crop rotations.

10.3.5 Management of N in agro-ecosystems

There are many management factors that affect N use efficiency in crop production. They can roughly be grouped into strategies that try to either (i) increase plant demand, (ii) manipulate supply or (iii) capture excess inorganic N before it is lost. The most obvious strategy is to adjust the N inputs as closely as possible in time and space to the requirements of the crop. However, to ensure an efficient N uptake requires a healthy crop, which is one of the most important, but often overlooked factors by which plant N demand can be increased. Break crops in temperate wheat production not only improve yield by improving N supply, but also by ensuring a healthier root system that enables the crop to better utilise soil N (Kirkegaard *et al.*, 2008). Similarly, leaf diseases in cereals have been found to reduce N use efficiency (Olesen *et al.*, 2003).

Soil tillage leads to disturbance of soil structure and this influences N turnover in the soil by modifying aeration and soil moisture that affects plant roots and soil organisms. Tillage also leads to a better mixing of soil and N-containing substrates that will favour decomposition and subsequently lead to release of mineral N. Soil tillage in autumn therefore often leads to enhanced losses of NO_3^- through leaching, whereas tillage in spring can lead to enhanced uptake of N by the crop, but also to greater N_2O emissions (Chatskikh and Olesen, 2007).

Water availability is one of the key factors controlling N processes (nitrification, denitrification, mineralisation, N leaching, etc.) and crop yield. This factor can be controlled more effectively in irrigated than in rain-fed systems. The intensification of irrigation to obtain economical benefit has grown in many areas, especially in arid and semi-arid regions, where a large amount of N fertiliser is often combined with a high volume of applied water. This has had an adverse effect on leaching losses contributing to groundwater pollution in important areas of these countries (Diez *et al.*, 1994), but good agricultural practices have emerged in response to the need to provide the right amount of water for each crop, avoiding therefore, as much as possible, over-watering (A. Vallejo, personal communication).

It is pertinent to make a special note at this point on the debate and the issue of sustainability of organic and conventional farming. Because organic farms do not use synthetic fertilisers, they have in general a lower yield per hectare than conventional farms. Comparing the emissions per unit of production provides more insight in both systems. Probably the best comparison will be made with an equal N intensity per hectare on organic and conventional farms, as has been discussed by Goulding *et al.* (2008) and Olesen *et al.* (2006).

10.3.6 Crop rotations

Crop rotations affect N use and losses in several ways. First, the rotation defines the sequence of crops of various N demands and of various amounts of N in residues returned to the soil. Second, the crop sequence defines the time of break between the different crops, time of tillage operations and possibilities (and needs) for growing cover crops. Third, the crop sequence affects crop growth by modifying soil properties and preventing (or propagating) weeds and diseases. The challenge is to design crop rotations that both maximises crop production (usually driven by the need to generate acceptable incomes) and, at the same time, reduces N losses. For grassland systems this may include avoiding late season grazing, high protein supplementary feeds and autumn ploughing of grasslands. For arable cropping, this could mean reduced autumn tillage, use of cover crops and spring application of manure with application technologies to reduce NH_3 volatilisation.

Intercropping with mixtures of two or more species is also effective in reducing risk of N losses, e.g., for grass-clovers compared with ryegrass monocultures (Eriksen *et al.*, 2004). Crop rotations that include grass or grass/clover leys require special care; there is an accumulation of organic N in the soil under the ley N management of the crop following the grassland needs to take account of the substantial net mineralisation that results when the grassland is ploughed (Eriksen *et al.*, 1999; Hutchings *et al.*, 2007). Under a sustainable agriculture management therefore, crop rotation is an important tool to improve nitrogen use efficiency. There is a greater degree of synchronisation between crop N-uptake and N dynamics in rotations than in monocultures (Pierce and Rice, 1988).

Cover crops (or catch crops) are crops that are grown in breaks between main crops, often to capture excess soil mineral N or to capture N by biological fixation (green manure crops). Both types of cover crops reduce N leaching when growing during the wet part of the year, when no main crop is present. The efficiency with which excess N is taken up depends on time of establishment and final root depth of the cover crop. Cover crops when used in the spring do not always lead to positive effects on crop N nutrition, since those with a large C:N ratio may lead to microbial immobilisation of N, and soils without a cover crop often have a higher initial mineral N content than where a cover crop has been growing (Thorup-Kristensen, 1994). In systems dominated by spring-sown cereals, cover crops can be established as an under-sown crop or sown just before harvest of the main crop. Such cover crops are therefore grown during autumn and winter and ploughed in spring, enhancing the synchrony of N uptake and supply, thereby reducing N leaching losses (Figure 10.9).

Cropping systems for ruminant husbandry provide plant biomass for grazing and for feed for housed animals. Animal grazing has traditionally relied on perennial leys of grass mixtures and grass-clover. However, with more intensive systems such leys may be included in the crop rotation, which further enhances N cycling and also the risks of losses. There is typically a non-linear relationship between input and output and, conversely, between input and losses (Figure 10.10). Above a certain N input, there is no further increase in productivity and N losses increase.

In intensive systems, grazing management is a key factor for N use efficiency on dairy farms. Restricted grazing contributes to increasing nutrient use efficiency at farm level through better utilisation of animal excreta, because these are collected in manure stored instead of being deposited in the meadow. However, in general, increasing the actual grazing period leads to smaller emissions of NH_3 and to greater leaching of NO_3^- and greater consumption of manufactured fertiliser. Increasing the grazing period also means fewer possibilities for adjusting the protein content of the animal feed. Finally, grazing is cheaper than housing and benefits animal welfare. For a comprehensive comparison of grazing-based and confinement-based cattle production we refer to the literature (Arsenault *et al.*, 2009). In extensive farming systems, grazing management has multiple goals including sustainability in terms of animal feeding resources and ecological and sociological functions (Hadjigeorgiou *et al.*, 2005).

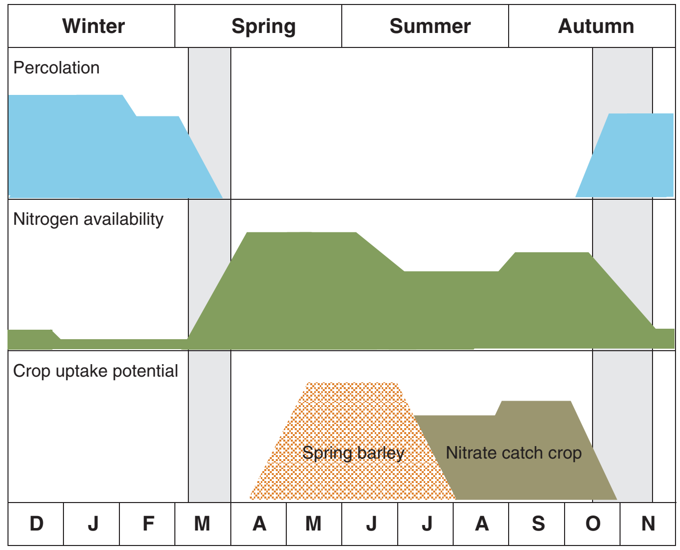

Figure 10.9 The seasonal dynamics of potentials for percolation (NO_3^- leaching loss), availability of mineral nitrogen (mineralisation + external inputs) and crop uptake under typical northwest European climatic conditions. The spring barley crop is under-sown with ryegrass acting as a catch crop. The vertical grey zones indicate periods with increased susceptibility to elevated NO_3^- leaching losses (from Christensen, 2004).

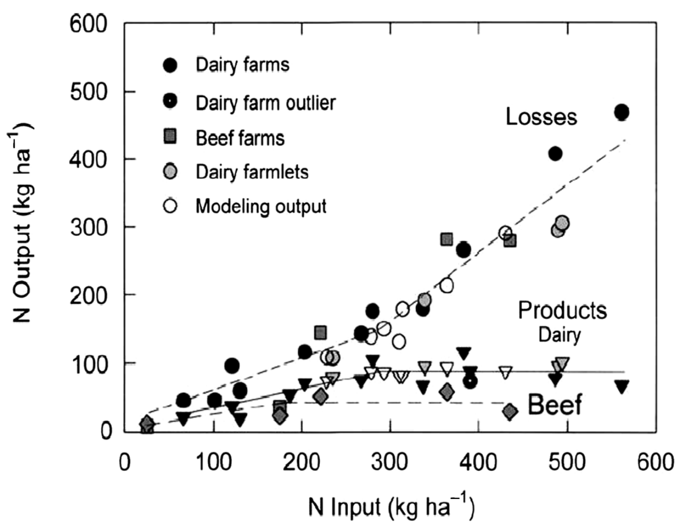

Figure 10.10 Relationship between total annual N input and N output as products (milk, meat and crops – shown as triangles) and as losses (volatilisation, denitrification, run-off, leaching and transfer to unproductive areas – shown as circles) in dairy and beef production systems that involve some grazing (from Rotz *et al.*, 2005).

10.3.7 Use of modelling

Process-based knowledge of N and C cycling has, in many instances, been integrated into mechanistic and dynamic simulation models, many of them operating at farm and agro-ecosystems scales. Models are often used for decision making at the macro policy level, but not necessarily for on-farm management. They therefore frequently influence bigger scale policy decisions, but not those concerned with production on farms on a widespread basis.

However, such models offer the potential to analyse the contribution of individual components to the total system N cycling and losses. This is typically done through sensitivity analyses and inter-model comparisons, which may be used to identify gaps in current process understanding. Modelling can also serve as a tool for interpreting experimental results and extrapolating to new environmental and management conditions (Smith *et al.*, 1997). The available models often have different strengths in scale or loss pathways. Most models function at the plot or field scale (Li *et al.*, 1992), whereas a few models integrate interactions also at the farm scale (Berntsen *et al.*, 2003; Brown *et al.*, 2005; Rotz *et al.*, 2005). Most of the models simulate NO_3^- leaching, some simulate denitrification and N_2O emissions (Li *et al.*, 1992), whereas few models simulate NH_3 volatilisation (Sommer *et al.*, 2003). Models are often applied for estimating losses at larger spatial or temporal scales. However, for feasibility this often involves simplifying model inputs or model structure. These models are rarely applied to practical decision support since they have large requirements on the accuracy of input data that cannot be met in practice. Instead more simple and empirical tools are used that rely on N balance sheets, supported by book-keeping of easily measured and estimated field or farm-scale inputs and outputs of N (see Sections 10.1 and 10.4). This is often supplemented with use of N response curves from field experiments and various approaches that apply N use efficiency considerations. These systems are, however, far from perfect and far from widespread, and there is particular need to improve the estimation of how much mineral N is released from mineralisation of soil OM and incorporated crop residues and catch crops.

10.4 Example farming systems

In this section, we consider the farm budgets of a range of farming systems. We focus on typical farming practice in north-western Europe and use information from various sources and expert opinions to model and construct generalised budgets (further information is provided in supplementary material for this chapter). The examples were chosen to illustrate some general differences between farming systems; it is therefore necessary to emphasise here that, in practice, a wide range of budgets can be found within each system type. The numbers in each Figure refer to annual flows of N per ha within the system.

10.4.1 Arable farms

The simplest budget is that of conventional arable farms (Figure 10.11). Production is largely driven by the use of imported mineral N fertiliser, although in areas containing livestock farms, imported manure may be an additional N source. The input of N via fixation is usually small unless it is an organically based system, since the crop rotation is usually dominated by non-fixing crops. Unless manure is imported or urea is the choice of fertiliser, NH_3 emissions will be relatively low. The fate of the remaining mineral N is divided between crop uptake, loss to the atmosphere as N_2, N_2O and NO via denitrification, loss in water as NO_3^- and DON in leachate and runoff or accumulation in SOM. The soil organic matter is also a source of N via mineralisation.

Over longer periods (annually or more), the balance between mineralisation and immobilisation in SOM is dependent upon the extent to which soil processes have reached an equilibrium with soil management and climatic conditions. The factors encouraging net immobilisation include the presence of crops or use of management practices that add larger amounts of plant residues (e.g., the presence of grass or the incorporation of straw), increased waterlogging (e.g., from changes in climate or drainage) and acidification (because of base-ion leaching). The proportion in crop uptake tends to increase as the growth potential of the crop increases (e.g., more productive varieties) and the proportion of the year in which a crop is established increases (e.g., through the use of crops with a long growing season or via the planting of catch crops). The partitioning of N between NO_3^- leaching, runoff and denitrification is dependent on a wide range of factors, including the type and timing of fertiliser addition, the soil type and drainage and the climate. In general, it appears that on freely-drained soils, NO_3^- leaching predominates whereas on poorly-drained soils and those with a high water table, denitrification predominates.

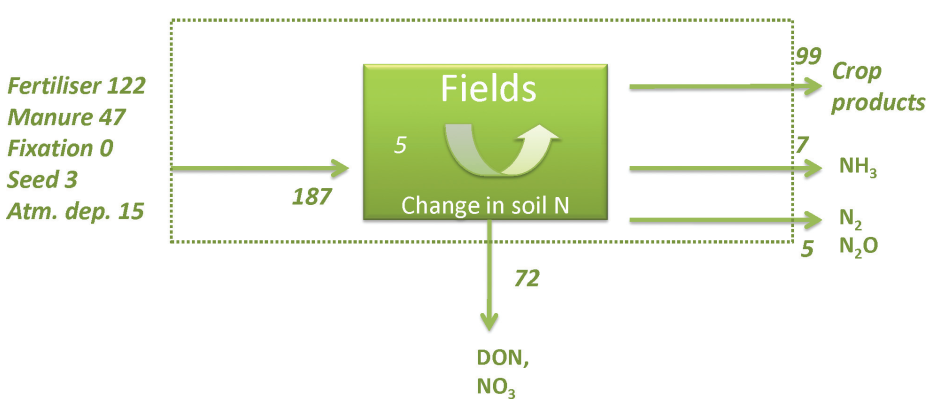

Figure 10.11 Annual nitrogen flows (kg/ha) in a conventional arable farming system.

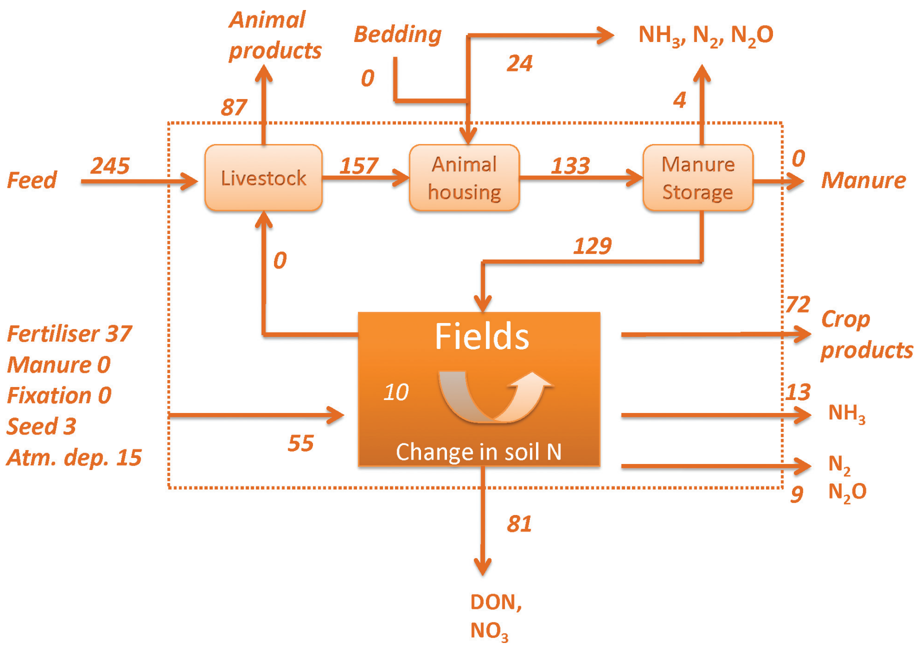

Figure 10.12 Annual nitrogen flows (kg/ha) in a pig farming system.

Recovery of N in crops and the fate of the un-recovered N should be estimated by measurement where it is technically and economically possible and modelling where it is not. In practice, a combination of both is the norm. It is important that estimates are not only based on experimental results, where conditions are usually close to optimal, but also from commercial farms where they may not be. Figure 10.11 shows values for Danish agriculture, so are typical for North West Europe and balanced N addition designed for yields that are about 10% below the economic optimum. Inputs and outputs were measured whereas the partitioning of the farm N surplus is based on assumptions that are reasonable for Danish agriculture. Note that leaching is estimated at the base of the root zone; the subsequent fate of the leached NO_3^- and DON is not determined in this example. The partitioning is particularly sensitive to the climatic and soil conditions. For example, in situations where the upper limit of the groundwater is within the root zone for part of the year, leaching would be much smaller and gaseous emissions from denitrification much greater. In the absence of balanced fertiliser inputs, the removal of N in crop would be marginally greater, but the losses to the environment would probably be substantially greater.

10.4.2 Livestock: non-ruminants

On farms with pigs, poultry and other non-ruminants, there is a substantial additional input of N in the feed imported for the livestock which supplies most or all of their requirements. Figure 10.12 shows an example of this for pig farms. As for arable farms, the input of N via fixation is usually limited. The large quantities of manure produced can sometimes be difficult to utilise effectively on the farm, so manure may have to be exported from the farm. If manure is exported, not all of the losses of N associated with the livestock production will be reflected in the farm N budget, since a proportion will occur on the farm receiving the manure. The values in Figure 10.12 are typical for the Danish situation in terms of climate, soils and balanced N fertiliser management. As a consequence, the import of N in mineral fertiliser is less than for the arable farm. As for the arable example, the farm inputs and outputs are based on measurements whereas the partitioning of the farm N surplus is based on assumptions that are reasonable for the Danish situation.

10.4.3 Livestock: ruminant animals

A proportion of the diet of ruminant animals is normally in the form of roughage (high-fibre plant material), because such feeds are required for good rumen function and because it is often relatively cheap compared with the alternatives. Roughage feed is usually bulky and therefore expensive to transport, so is usually produced on the farm rather than imported. On specialist ruminant livestock farms, much or all the farm's land will be dedicated to growing roughage feed, so a large proportion of the diet is produced on the farm (Figure 10.13). If the livestock manure is applied to this land, this creates a feedback mechanism in which the amount of N in the feed affects the amount in the manure, which affects the N supplied to the roughage and therefore the N content of the roughage fed to the animals. Ruminant livestock farms also differ from non-ruminant farms in three other aspects. The first is that a proportion of the roughage feed is often harvested by grazing, so the N deposited in the accompanying dung and urine bypasses the manure management system. The second is that the feed conversion efficiency for the ruminants is generally poorer than for the non-ruminants. This in part reflects the inherently lower efficiency of the ruminant digestion and in part the tendency for the inclusion of roughage in the diet to lead to an oversupply of protein. The third difference is that it is not uncommon to include plants such as clover in the roughage crops, so the input of N from fixation may be greater than on other types of farms.

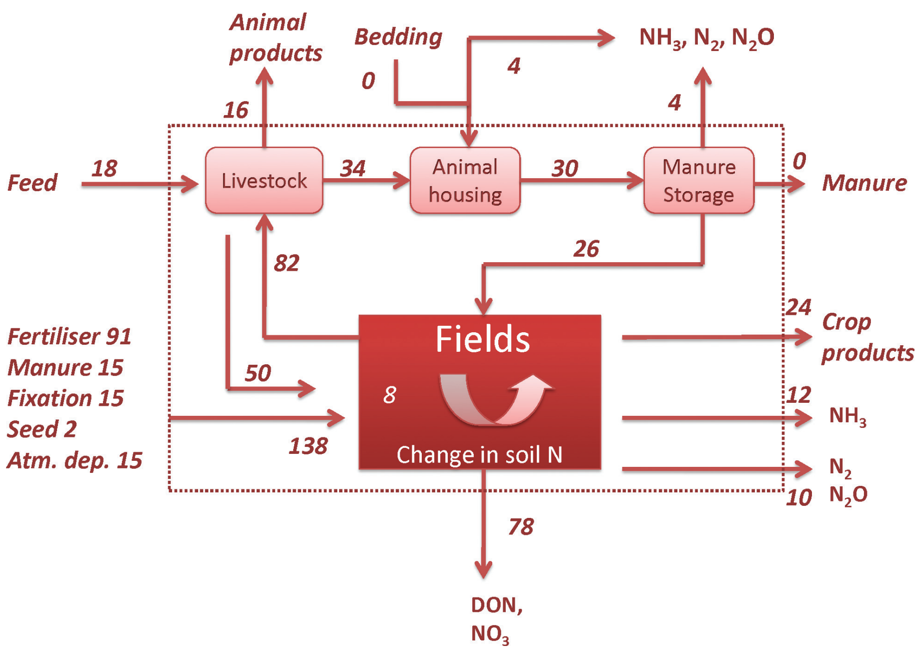

Figure 10.13 Annual nitrogen flows (kg/ha) in a beef farming system.

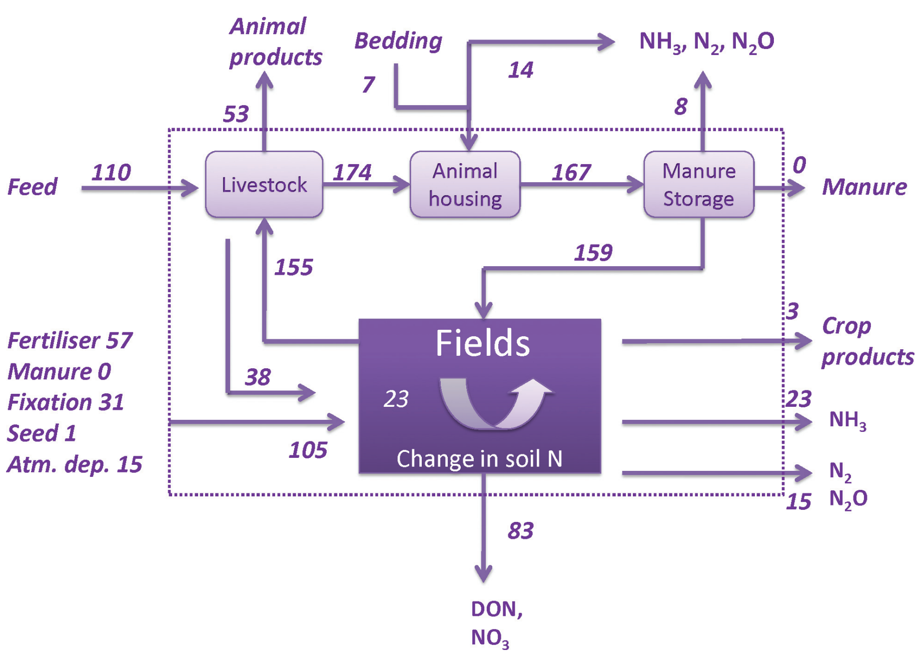

Figure 10.14 Annual nitrogen flows (kg/ha) in a dairy farming system.

Figure 10.13 illustrates the N flow on a beef farm where grazed herbage is a major component of the animals' diet. As a consequence, there are significant flows of N from the pasture to the cattle via grazing and from the cattle to pasture *via* the associated deposition of dung and urine. Because the animals spend a large proportion of the year at pasture (here assumed to be 0.6), the amount of N managed as manure is small, relative to that typical for pig farms. As a consequence, the gaseous emissions of N are also smaller but the leaching losses are larger.

On intensive dairy farms (Figure 10.14), the energy demand of highly productive livestock cannot be satisfied by roughage alone, so feed with a high energy concentration (e.g., grain) will be imported onto the farm. The proportion of the animal feed demand satisfied from the farm's resource is therefore smaller than for more extensive ruminant systems, such as the beef system (Figure 10.13). Although the young replacement cattle will often be grazed for much of the year, the dairy cows will spend a significant proportion of time in animal housing, even during the growing season. The weighted average proportion of time spent indoors is assumed here to be 0.4. As for the pig farms, large amounts of manure are produced in the animal housing, leading to substantial losses of gaseous N. Despite the differences between the example beef and dairy situations in the magnitude of individual inputs and flows of N, the total amount of N entering the soil are similar in both

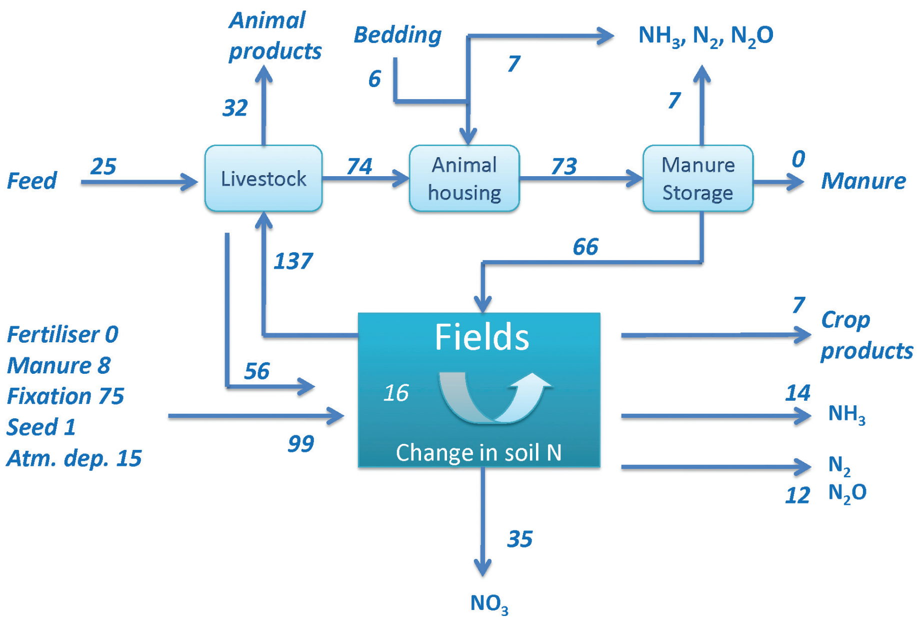

Figure 10.15 Annual nitrogen flows (kg/ha) in an organic dairy farming system.

cases. As a consequence, losses by leaching and denitrification are similar.

The final example shown here is of organic dairy farming (Figure 10.15). The main distinguishing management features of the organic dairy farm as far as N flows are concerned, are the lower intensity of production and the absence of mineral fertiliser inputs. The reduced intensity leads to a greater contribution of N fixation to the N input to the crops and a greater efficiency of recovery in the offtake from the farm in animal products and crops from all external inputs to the soil (about 30% compared with 25% for the conventional dairy farm). There is also a greater accumulation of N in the soil than found for the other farming types. The consequent reduction of losses of N to the environment is therefore the result of a combination of a lower stock density and a greater efficiency of N use in the field.

It can be noted that although the typical total losses of N to the environment in the organic system (75 kg/ha) are much smaller than the conventional dairy farming system (Figure 10.14) (143 kg/ha), there are also substantial differences in the total products produced. Thus the total animal and crop products of the organic system in Figure 10.15 contain 39 kg/ha N, while those of the conventional system in Figure 10.14 contain 56 kg/ha N. Expressed as losses of N to the environment per unit N in products, the losses are about 30% greater in the organic example (ratio of 2.5) compared with the conventional dairy (ratio 1.9) (Table 10.1).

The comparison above is with an organically based system, but it is likely that similar differences between dairy managements would be obtained when other low-input systems are compared with those based on greater levels of input. Table 10.1 provides a summary of the differences in annual losses from the farm budgets described in this chapter and indicates some other important differences. For example, whilst there are some substantial losses from the pig farm, the ratio of loss to that in the product is relatively much smaller than that in the beef system. However, caution is needed in interpreting these ratios. For example, pig production has a smaller ratio than beef but this is because these farms import large quantities of animal feed and the emissions associated with the feed production occur in another farm. In contrast, the cattle farms produce a larger proportion of the animal feed themselves.

10.4.3 Other farming systems

The previous estimates have, of necessity, centred on NW European examples for which there is a growing bank of information on the various components comprising a farm system. This is not the case for systems in many other parts of Europe, especially those in the south and also for many of those based on low input managements. As an example, in southern European farms, the N balance and flows are very dependent on soil moisture conditions and whether the crops are irrigated or rain-fed. The effects of the warmer temperatures and different moisture status on N flows can result in very different effects to those described earlier. For example, in areas close to intensive livestock production, such as pig farms where slurry is often used to supply N instead of mineral N, effects of moisture and temperature can be accentuated. Thus, although the N balance is quantitatively very similar when mineral N is applied, depending on the slurry management (rate, timing, method of application, etc.), the relative importance of pathways of N flows and losses may be very different, particularly those of NH_3 volatilisation (A. Vallejo, personal communication).

Other information for systems in other parts of Europe is given in De Clercq *et al.* (2001), which provides simple farm-gate balances for typical farming systems in each of the EU-16 countries. Whilst such balances provide useful insights into the N surpluses for a wide range of farming systems and their efficiency of N use, they are based on limited

Table 10.1 Summary of annual N in products and losses (kg/ha) derived from the typical farm nitrogen budgets (Figures 10.11–10.15), with losses also expressed per unit N in products

Farm management	Nitrogen in crop and animal products	Nitrogen losses	N losses per unit N in products (as ratio)
	kg/ha/year N		
Arable	99	84	0.85
Pig	159	131	0.82
Beef	40	108	2.7
Dairy (conventional)	56	143	2.55
Dairy (organic)	39	75	1.92

data and do not, for example, illustrate the internal transfers that occur and can be seen in the earlier examples. There is therefore much scope to gain wider understanding for these systems and thus identify opportunities to improve N management and reduce flows to the wider environment under other circumstances.

10.5 Conclusions

- Nitrogen is an essential component of the requirements for producing food, fibre and energy. There is no opportunity of avoiding inputs from some source or other without reducing production potential. As a consequence, there will always be some losses: natural ecosystems also leak N into the wider environment. It therefore takes much skill and effort and is difficult, but by no means impossible, to reconcile the dual aims of sustaining or increasing production with an ever-increasing demand for reduced losses to the environment when there is an increasing demand for food.
- Farming systems within the EU are diverse, occupying wide ranges of climate, soil type, topography and managements. Our examples have centred on current farming practice in parts of NW Europe. Those operating in Southern Europe will have very different objectives, operational structures and, although the same mechanisms and pathways for N are involved, different flows of N will be encountered as demonstrated in the examples of farm-type budgets.
- The role of the individual farmer is crucial in optimising the flows of N to meet the dual targets of maximising production and minimising environmental cost. The aim must be to optimise supplies to the crops and animals by more effectively matching supply and demand, in time and space.
- The farm N-cycle, which we have described in fairly simplistic terms, is actually rather complex: each component of the cycle can be divided into other internal cycles, which may be more or less complex. Equally, the farm cycle is a smaller component of the larger-scale cycling that occurs and which is generally considered at catchment or river-basin scales. Superimposed on all of these scales is societal influence, which can be multi-directional in its effects, requirements and impacts. The farm scale is, however, the operational scale at which many of these interactive effects are demonstrated or at which implementation policies have to be deployed, either for production or environmental requirements.
- Livestock farming presents particular issues and problems and, particularly where it is separated from tillage land, can result in accumulations of N with the potential of overloading the system and generating much leakage of excess N. Again technologies are available and are being increasingly employed to reduce the impact of, for example, NH_3 volatilisation.
- Agriculture and the technologies that it employs have reacted positively to the changes required to meet the demands placed upon agriculture. Decision-making in the use of N has become more precise, but there is opportunity to do more. However, there are limits to the increases in efficiency that can be achieved (see Figure 10.4). Important in achieving the potential to increase the efficiency of N use is the maintenance of a high skill base and awareness of environmental impacts amongst the farmer community.

The benefits of using N effectively on farms are important and large. The strengths of using N are that it has immediate impact in promoting growth and production, that we know a great deal about its controls and flows, and that it is also a very effective management tool for farmers to provide flexibility and other requirements. The weaknesses of using N are that it is a very mobile and leaky nutrient, it is readily available (although at cost) and easy to use, but does require skilled management. There are increasing opportunities to employ ever-developing technologies to maximise efficiencies (precision application of fertilisers and manures, improved animal diets, improved breeding to optimise supplies, etc.) and an ever-increasing knowledge base amongst land managers about the requirements for its use from both production and environmental perspectives.

There are, however, continued threats to the use of nitrogen in agriculture, which may involve complex interactions and feedback mechanisms with climate change, while possible future revised environmental standards may put increased demands on farmers to reduce losses further. Finally, changing price structures for inputs (including N fertilisers) and the goods produced, coupled with other public pressures, may make the challenges for using N even more demanding.

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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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