Principles of overall nitrogen management

Background document

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Introduction

The purpose of this draft document is to provide background information, principles and guidelines for integrated nitrogen (N) management in agriculture. It is meant as "fuel" for discussion at the DG ENV/TFRN workshop to be held in Brussel, October 11-12, 2016. The purpose of the workshop is briefly '*to explore options for a more integrated management so as to achieve the targets for ammonia emission reduction, for nitrate leaching losses to groundwater and surface waters, and for nitrous oxide emission reduction in a more effective and efficient way, while synergistic side-effects related to air and water quality, climate change, biodiversity, human health are being achieved at the same time*'.

The content of this document has been derived and copied from various reports, including:

- Bittman, S., Dedina, M., Howard C.M., Oenema, O., Sutton, M.A., (eds), (2014), *Options for Ammonia Mitigation: Guidance from the UNECE Task Force on Reactive Nitrogen*, Centre for Ecology and Hydrology, Edinburgh, UK.

- EU Nitrogen Expert Panel (2015) Nitrogen Use Efficiency (NUE) - an indicator for the utilization of nitrogen in agriculture and food systems. Wageningen University, Alterra, PO Box 47, NL-6700 Wageningen, Netherlands.

- Anonymous (2011) Recommendations for establishing Action Programmes under Directive 91/676/EEC concerning the protection of waters against pollution caused by nitrates from agricultural sources (ND-Act). Alterra, Wageningen-UR, Wageningen. 33 pp.

- Oenema et al. (2011) Developing integrated approaches to nitrogen Management. Chapter 23 in The European Nitrogen Assessment, eds. M. A. Sutton, C. M. Howard, J. W. Erisman et al. Cambridge University Press.

Nitrogen management

Nitrogen (N) is essential for life and plays a key role in food production. Nitrogen is the most important crop-yield limiting factor in the world, together with water (Mueller et al., 2012). That is why farmers apply N fertilizers, which became available and affordable in affluent countries from the 1950s and more recently in almost all countries (Smil, 2000). However, too much N leads to pollution, which is harmful for the functioning of our ecosystems and our health (Box 1). The management of N is therefore important, especially in agriculture, which is the biggest user of N in the world.

Nitrogen management in agriculture aims at achieving agronomic objectives (farm income, high crop and animal productivity) and environmental objectives (minimal N losses) simultaneously. However, N management is not easy, because the N cycle is complex (Box 2) and N is easily lost from agriculture into the environment. Nitrogen is a constituent of all plant and animal proteins (and enzymes) and it is involved in photosynthesis, eutrophication, acidification and various oxidation-reduction processes. Through these processes, N changes in form (compounds), reactivity and mobility. Main mobile forms are the gaseous forms di-nitrogen (N_2), ammonia (NH_3), nitrogen oxides (NO and NO_2), and nitrous oxide (N_2O), and the water soluble forms nitrate (NO_3^-), ammonium (NH_4^+) and dissolved organically bound N (DON). In organic matter, most N is in the form of amides, linked to organic carbon ($R\text{-}NH_2$). Because of the mobility in both air and water, N is called “double mobile”.

Integrated nitrogen management emphasizes the need to manage nitrogen in an integrated manner. The notion that N needs to be managed in a comprehensive and integrated way follows from the understanding that reactive nitrogen (N_r) once formed is involved in a sequence of transfers, transformations and environmental effects (e.g., Galloway and Cowling, 2002; Galloway et al., 2008), that the economic costs of emissions abatement are often high, and that the management of a single source and/or a single N_r species, especially agriculture, is not always efficient, and that nitrogen management also affects the cycling of other elements, including carbon (C), phosphorus (P) and sulphur (S). Fundamental arguments for using integrated approaches to N management follow also from the first and second law of thermodynamics. Basically, the first law implies that the element N can be transformed into different species, but it cannot be ‘destroyed’. The second law of thermodynamics basically implies that N has the natural tendency ‘to dissipate’ into the environment. Nitrogen has been termed ‘double mobile’, together with carbon and sulfur (Smil, 2001), because these elements are mobile in both air and water (and soil).

Though there is scientifically sound underpinning for considering the management of the various N sources in a more holistic and integrated manner, there are also barriers and constraints for more integrated approaches, such as the compartmental and discipline oriented structure and organization of policy departments and science groups. There is also discussion about ‘what and how to integrate?’ In EU policy, there is an increasing tendency for developing more integrated (economic-environmental) approaches, but many current environmental policies still have a narrow scope as regards N management. The discussion is in part also confused by lack of clear and accepted definitions about the terms ‘integrate’ and ‘management’. Integration is perceived as combining separate elements and aspects in an organized way, so that the constituent units function cooperatively (see supplementary information to this chapter). There are various integrated approaches to N management in practice, with various degrees of combining separate elements and aspects. There are at least 5 different dimensions of integration in N management, namely: (i) vertical integration, (ii) horizontal integration, (iii) integration of other elements, (iv) integration of stakeholders’ views, and (v) regional integration.

Box 1. Nitrogen is essential for life but too much nitrogen is harmful

Nutrient elements are essential resources for food, feed and biofuel production, next to energy, carbon dioxide, water, biodiversity, labour, capital and management. Plants require 14 nutrient elements, in specific amounts, for proper growth and development. Animals and humans require some 22 nutrient elements in specific quantities, for proper growth and development.

Nitrogen (N) is a main nutrient element and needed in relatively large quantities for the production of amino acids (protein), nucleic acids and chlorophyll in plants. Nitrogen occurs in different forms in soil, air and waters, but only a few N forms are directly available for uptake by plant roots. The availability of N is often limiting food, feed and biofuel yields; it is one of the elements that is most limiting biomass production in the world.

The invention of the Haber-Bosch process, more than 100 yrs ago, marks a major change in the global N cycle, as it allowed the large-scale production of synthetically produced N fertilizers from di-nitrogen (N_2) in the atmosphere. Relatively cheap N fertilizers came on the market from about the 2^{nd} half of the 20^{th} century, especially in affluent countries. The increased use of N fertilizers has contributed greatly to the increased global food, feed and biofuel production, needed for the increasing human and animal populations (Smil, 2000).

Global N fertilizer use has increased from about 10 Tg in 1961 to almost 110 Tg in 2012 (Figure 1), but there are large differences between continents. Fertilizer N use in Africa is staggering at a level of about 1-2 Tg per year during the last decade, while fertilizer N use in Asia has increased during last three decades by on average 2 Tg per year. Fertilizer N use in Europe increased fast between 1950 and 1990, but stabilized thereafter at a level of about 10 Tg per year (Erisman et al., 2008; Sutton et al., 2011; Sutton et al., 2013). The rapid decrease in European N use around 1990 is mainly due to the political restructuring of Eastern and Central Europe at this time. The slow decrease in fertilizer use in Europe between 1990-2010 is related also to EU agri-environmental policy.

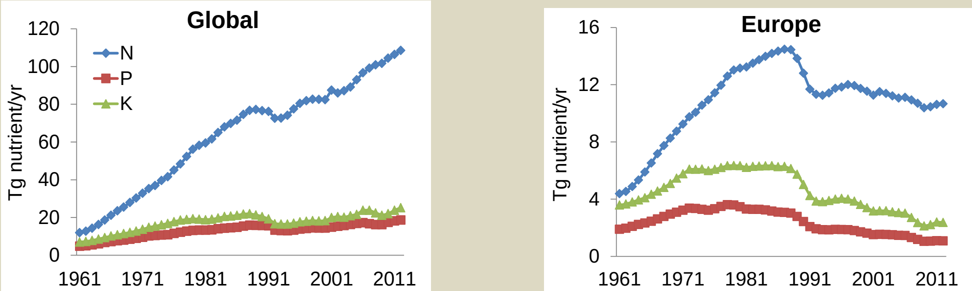

Figure 1. Changes in Fertilizer N, P, K use in the world and Europe during 1961-2011 (FAOSTAT, 2015)

The availability of N in agriculture increased during the last 100 yrs also through the production of leguminous crops (beans, pulses, clover and alfalfa) that fix N_2 biologically, through energy combustion that increases atmospheric NO_x emissions and N deposition, and through the increasing production of animal manures, and of residues and wastes from industries and households (Herridge et al., 2008; Davidson, 2009; Sutton et al., 2013).

The increased availability of N in agriculture has also increased the losses of N to the wider environment, to air and water bodies. Emissions of N to the wider environment occur via various N forms (Box 2; e.g., NH_3, N_2, N_2O, NO, NO_3^-), which can lead to problems related to human health and ecosystem degradation. The volatilization of ammonia (NH_3), leaching of nitrate (NO_3^-), and the emissions of di-nitrogen (N_2), nitrous oxide (N_2O) and nitrogen oxide (NO) following nitrification-denitrification reactions are the main N loss pathways from agricultural systems and food systems. These N forms (except N_2) are often termed “reactive N”, as they are biologically, photo-chemically and/or radiatively active N compounds. Possible human health and environmental effects of this reactive N include (Galloway et al., 2008; Sutton et al., 2011) a decrease of human health, due to NH_3 and NO_x induced formation of particle matter ($PM_{2.5}$) and smog, plant damage through NH_3 and through NO_x induced tropospheric ozone formation; a decrease of species diversity in natural areas due to deposition of NH_3 and NO_x; acidification of soils because of deposition of NH_3 and NO_x; pollution of groundwater and drinking water due to nitrate leaching; eutrophication of surface waters, leading to algal blooms and a decrease in species diversity; global warming because of emission of N_2O; and stratospheric ozone destruction due to N_2O.

Box 2. The Nitrogen Cycle

Nitrogen (N) occurs in different forms and transforms from one form into the other almost endlessly (Figure 2). Molecular nitrogen (N_2) is the dominant constituent of our atmosphere and the most abundant N form on Earth. Only a few microorganisms have the capability to utilize (fix) N_2, converting it to organically bound N. The Haber-Bosch process converts N_2 into ammonia/ammonium (NH_3/NH_4^+) in a physical-chemical manner. The NH_3/NH_4^+ can be taken up by plants (assimilation). Following the senescence of plants and organisms, the organic-N is transformed again into NH_3/NH_4^+ (through mineralization). Autotrophic bacteria can utilize the energy contained in NH_3/NH_4^+ through nitrification. Thereby, the oxidation status increases from -3 in NH_3/NH_4^+ to +5 in nitrate (NO_3^-). The NO_3^- can be taken up by plants (assimilation) or it is denitrified to nitrous oxide (N_2O) and to di-nitrogen (N_2) in anaerobic environments through heterotrophic bacteria. Molecular N (N_2) may be formed also through anaerobic ammonium oxidation (anammox; $NH_4^+ + NO_2^- \rightarrow N_2 + 2H_2O$), by chemoautotrophic bacteria in the deep sea.

Figure 3 presents a quantitative picture of the global N cycle. Large amounts of N cycle between atmosphere and the terrestrial and marine biospheres, via gaseous N forms. The N cycle is strongly linked with the carbon cycle and with other nutrient cycles, including phosphorus (P), and sulphur (S); managing N affects also the cycling of C, P, and S and the net release of CO_2 into the atmosphere and C sequestration in soils.

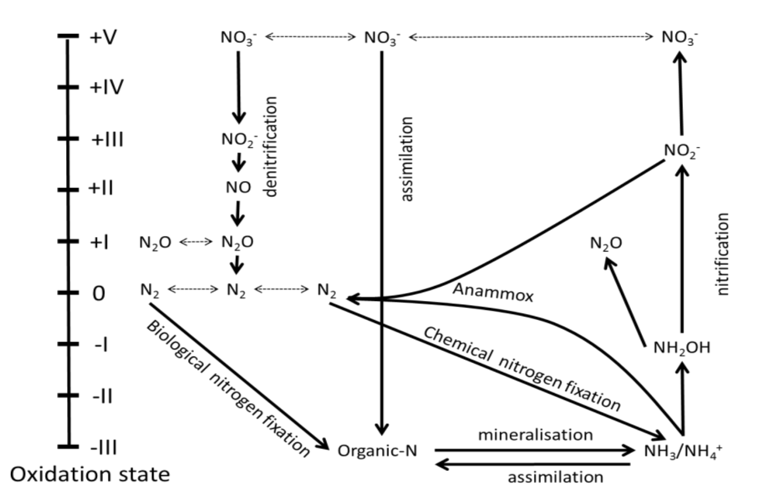

Figure 2. Processes of the N cycle and the related changes in the oxidation status of the N forms. The oxidation status (vertical axis) ranges from +5 in nitrate (NO_3^-) to +3 in nitrite (NO_2^-), to +2 in nitrogen oxide (NO), to +1 in nitrous oxide (N_2O), to 0 in di-nitrogen (N_2), and -3 in ammonia (NH_3), ammonium (NH_4^+) and amines (C-NH_2). The N forms NH_3, N_2, N_2O, NO, NO_X are gaseous at temperature at the earth surface; the N forms NO_3^- and NH_4^+ and some organic N forms (DON) are readily soluble in water. This makes N 'double mobile' (Smil, 2000)

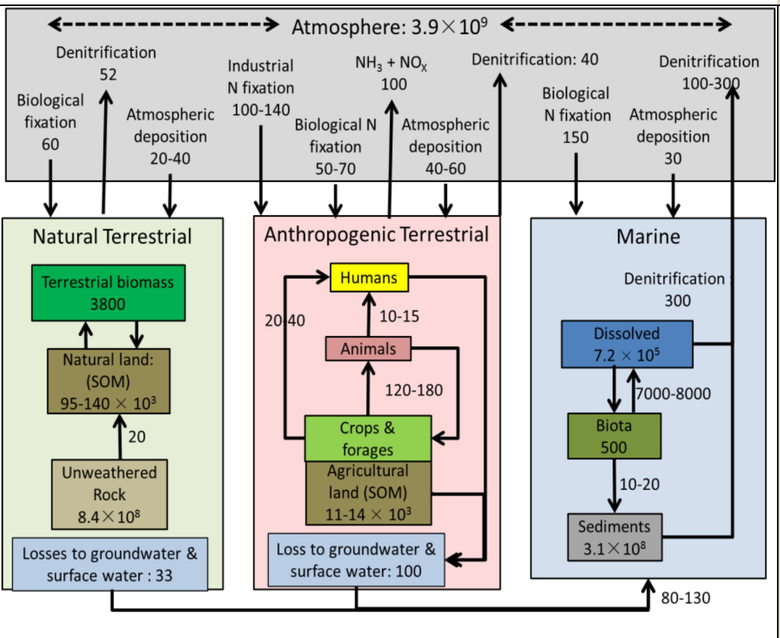

Figure 3. Global nitrogen cycle, showing the dominant flows of N between atmosphere and the natural terrestrial area, the anthropogenic area (agricultural + industrial + urban), and the marine area. Arrows indicate the approximate size of the N flows, in Tg N per yr. Numbers in boxes refer to the size of the N pool of that compartment, in Tg N. Note that the transport of N from anthropogenic sources to the natural terrestrial and marine areas occurs mainly via the atmosphere and rivers. The magnitude of some flows are rather uncertain. Compilation of data from Smil (2000), Fowler et al (2013), Schlesinger and Bernhardt (2013).

Dimensions of integration

Vertical integration in economy is the linkage of upstream suppliers to downstream buyers (Figure 4). Vertical integration results in more control, higher production efficiency and more marketing power. Vertical integration in ecology is the functional linkage of autotrophic producers to heterotrophic consumers (including herbivores, carnivores, omnivores and saprovores), expressed in the idea of a food chain. In terms of N management, vertical integration relates to linking 'cause and effect', and 'source and impact'. Examples of vertical integration are the 'driving forces, pressures, state, impact and response' framework (DPSIR-framework; see OECD, 1991; EEA, 1995) and the 'effects-based approach' to emissions abatement policies as applied in the Gothenburg Protocol (UNECE, 1999). Essentially, vertical integration is the basis of all current N policies in Europe, as the human health effects and ecological impacts are the legitimate of these policies, while the selection of abatement measures is based in part on the economic consequences (cost-effectiveness). Thus, the gains in human health and biodiversity are weighted against the cost of the emission abatement. A full cost-benefit analysis is still complicated, because of the difficulty of attaching monetary values to human health and ecosystems, although significant progress has been described in Chapter 22 (Brink et al., 2011, this volume). Evidently, including cost-benefit analyses would make vertical integration of N management more complete.

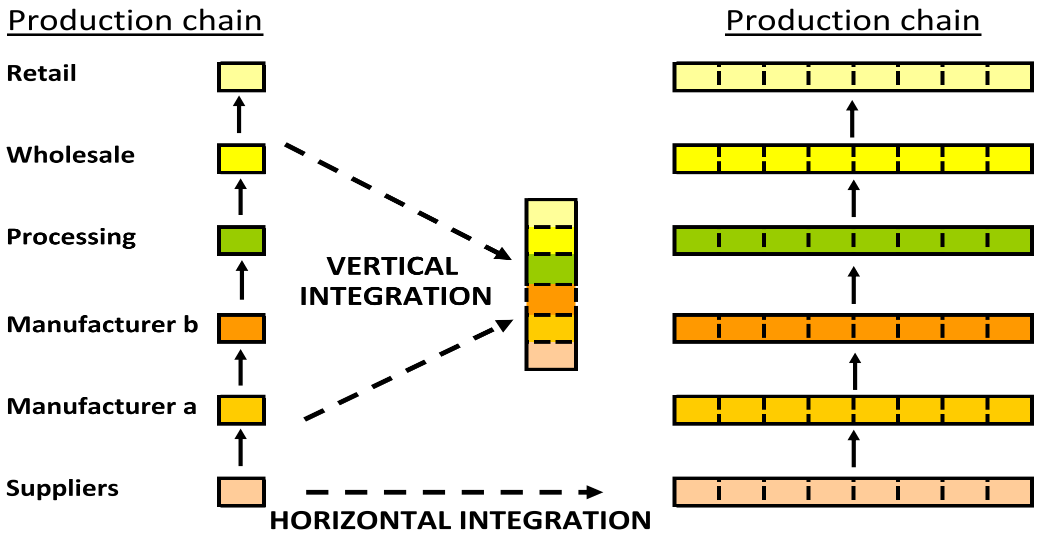

Figure 4. Conceptual visualization of vertical and horizontal integration of firms in production chains. (Source: original material for this chapter).

Horizontal organization is related to up-scaling so as to benefit from larger scale and number. Horizontal integration is the linkage of elements of similar entity, for example when similar firms merge to benefit from the economics of scale (Figure 4). Also the herding of animals, schooling of fishes, flocking of birds and colonies of ants and termites can be considered as forms of horizontal integration. Horizontal integration in N management relates to combining N species, N sources and N emissions within a certain area in the management plan. Partial forms of horizontal integration are in the Gothenburg Protocol (e.g., all anthropogenic NO_x sources and all NH_3 sources have been included, but N_2O emissions to air and N leaching to waters are not included) and the EU Nitrates Directive (all N sources in agriculture have to be considered for reducing NO_3 leaching to waters, but NH_3 and N_2O emissions to air are not addressed explicitly). Similarly, the emission of gaseous N_2 through denitrification is not considered in these policies. Although emission of gaseous N_2 does not lead directly to adverse environmental effects, its release can be considered as a waste of the energy used to produce N_r, indicating the need that N_2 emissions should also be addressed.

Conceptually, the N cascade model (Galloway et al., 2003; Sutton et al., 2011) is a nice example of horizontal integration, but this model has not been made operational for management actions yet. The N cascade is also a conceptual model for vertical integration, especially when cost-benefit analyses are included.

Integration of other elements and compounds. Emissions of nitrogen oxides (NO_x), ammonia (NH_3) and sulphur dioxide (SO_2) to air have rather similar environmental effects (air pollution, acidification, eutrophication), and that is the reason that the effects-based approach of the CLRTAP Gothenburg Protocol and the EU National Emission Ceiling Directive address each of NO_x, NH_3 and SO_2. Similarly, emissions of N_r and phosphorus (P) to surface waters both contribute to eutrophication and biodiversity loss, and thus EU policies related to combat eutrophication of surface waters address N and P simultaneously (Oenema et al., 2011). Further, the N and carbon (C) cycles in the biosphere are intimately linked, and the perturbations of these cycles contribute to increased emissions of CO_2, CH_4 and N_2O to the atmosphere. Climate change policies address these greenhouse gases simultaneously. Nitrogen may also affect CO_2 emissions through its effect on carbon sequestration in the biosphere and by alteration of atmospheric chemistry (Butterbach-Bahl et al., 2011,).

Evidently, there are two main reasons to integrate N management with the management of specific other elements (compounds) in environmental policy, namely (i) the other elements (compounds) have similar environmental effects, and (ii) interactions between N species and these other elements and compounds. From the practitioner point of view, there can be benefits when managing N and specific other elements simultaneously. This holds for example for NO_x and SO_2 (and soot) from combustion sources, and N and P in agriculture and sewage waste treatment.

Stakeholder involvement and integration. Any N management policy, whether integrated or not, needs to be: (i) policy-relevant; i.e., address the key environmental and other issues; (ii) scientifically and analytically sound; (iii) cost effective; i.e., costs have to be in proportion to the value of environmental improvement, and (iv) politically legitimate; i.e., acceptable and fair to users. When one or more of these constraints are not fulfilled, the management policy will be less effective, either through a delay in implementation and/or through poor implementation and performance. Satisfying the aforementioned constraints requires communication between actors from policy, science and practice. Tuinstra et al. (2006) argue that the credibility, legitimacy and relevance of the science-policy interaction are to a large extent determined by 'boundary' work in an early stage of the communication process between policy and science. They analyzed the communication process between policy and science in the Convention for Long-range Transboundary Air Pollution (CLRTAP) and the EU National Emission Ceiling Directive. Boundary work is defined here as the practice of maintaining and withdrawing boundaries between science and policy, thereby shaping and reshaping the science-policy interface.

Of similar importance is the communication with practitioners, i.e., the actors that ultimately have to execute management actions in practice. Integrating their views has to be done also as early as possible during the design phase of the N management plans and measures, because the practitioners, in the end, have to implement the management measures. Integrating views of practitioners may range from public consultation procedures, hearings to participatory approaches and learning; the latter take the practitioners' perspectives fully into account and give them a say also in planning and managing. A good example of the latter approach is the EU Water Framework Directive (EC, 2010), which requires full stakeholder involvement for the establishment of water basin management plans.

Integration of practitioners' views does not necessarily lead to faster decision making; on the contrary, the decision making process often takes more time. Public consultation procedures can be very long-winded, though techniques like multi-criteria decision making (MCDM) may support decision making effectively; this approach aims at deriving a way out of conflicts and to come to a compromise in a transparent process. Integration of practitioners' views may ultimately improve the acceptance of the management strategies, and thereby facilitate the implementation of the management strategies in practice.

Regional integration or 'integration of spatial scales' is considered here as the fifth dimension of integration. Regional integration aims at enhanced cooperation between regions. It relates to integration of markets and to harmonization of governmental polices and institutions between regions through political agreements, covenants and treaties (Bull et al., 2011). Arguments for regional integration are: (i) enhancing markets, (ii) creation of a level-playing field, (iii) the transboundary nature of environmental pollutions and (iv) the increased effectiveness and efficiency of regional policies and related management measures.

In terms of N management, regional integration relates, for example, to the harmonization and standardization of environmental policies across European Union and for air pollution in the UNECE region (Oenema et al., 2011; Bull et al., 2011). The water basin or catchment management plans developed within the framework of the EU Water Framework Directive are also a form of regional integration. Here, water quantity and quality aspects are considered in an integrated way for a well-defined catchment.

The trend toward regional integration during last decades does not necessarily mean that local management actions are less effective and/or efficient. Local actions can be made site-specific and, as a consequence, are often more effective than generic measures. This holds both for households, farms and firms, and especially when actors can have influence on the choice of actions. Also, the motivation for contributing to the local environment and nature can be larger than for contributing to the improvement of the environment in general (e.g., Kahn, 2001);

Tools for integrated approaches to N management

The toolbox for developing integrated approaches to N management contains tools that are uniformly applicable, as well as highly specific, suitable for just one dimension of integration. Important common tools are: (i) systems analysis, (ii) communication, (iii) N budgeting, (iv) integrated assessment modeling and cost-benefit analyses, (v) logistics and chain management, and (vi) stakeholder dialogue.

The starting point for developing integrated approaches is '**systems analysis'**, as it provides information that is needed for all dimensions of integration. Systems analysis allows for identifying and quantifying components, processes, flows, actors, interactions and inter-linkages within and between systems, and provides a practical tool for discussing integrated approaches to N management. In essence, it encompasses the view that changes in one component will promote changes in all of the components of the systems (e.g., Odum, 1996). These type of tools are being used especially by the science-policy interface.

A second tool for developing integrated approaches is communication. **Communication** is transferring information, but at the same time the tool for raising awareness and for explaining the meaning, purpose, targets and actions of integrated approaches to N management to all actors involved. Clear communication is important, as there is often ambiguity in the use of the terms 'integrated' and 'management' and insufficient clarity about the objectives and required actions. Communication can help make the concept transparent and thereby can facilitate the adoption of targets and measures in practice.

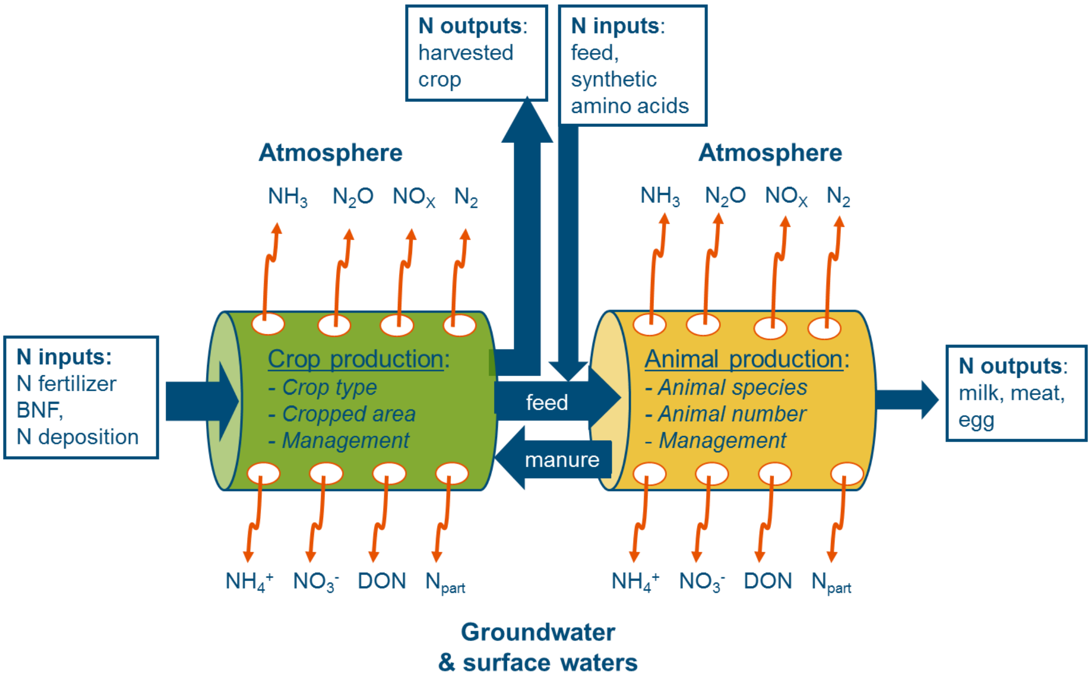

Figure 5. Concept of the nitrogen input – output mass balance of mixed crop – livestock production systems. The 'hole of the pipe' model illustrates the 'leaky N cycle' of crop and animal production; it shows the fate of N inputs in agriculture. Inputs, outputs in useful products and emissions to air and water show dependency in crop production and animal production; a change in the flow rate of one N flow has consequences for others, depending also on the storage capacity of the system. Total inputs must balance total outputs, following corrections for possible changes in storage within the system (Oenema et al., 2009)

A third type of tool is **nitrogen balances**, which quantifies the differences between nitrogen inputs and outputs of systems and of compartment of these systems. This is an indispensible tool for horizontal integration and in part also vertical integration; it integrates over N sources and N species for well-defined areas and/or components. The N balance records all inputs all outputs in marketed products, and the N surplus, the difference between total inputs and total output. The 'hole-in-the-pipe model' illustrates the leaky nature of the agricultural and food systems, i.e., there are many opportunities for N species to escape (Figure 5). The hole-in-the-pipe model also illustrates the importance of integrated N management; i.e., mitigation a N loss pathway will inevitably increase other N loss pathways (i.e., pollution swapping), unless the total output in harvested product is increased and/or the total N input decreased proportionally. Input-output balances can help to detect and illustrate pollution swapping. Input-output N balances have been proven to be easy-to-understand management tools for farmers (Jarvis et al., 2011), plant managers and policy managers (see supplementary information to this chapter). Input-output balances and budgets are flexible tools, but require uniform definitions and conventions to circumvent bias (Oenema et al., 2003; De Vries et al., 2011, Leip et al., 2011). Life Cycle Assessment (LCA) is an approach to account for emissions and resources during the entire life cycle of a product. It can be seen also as a tool for horizontal integration, similar as input-output budgets, but it integrates also over time. This type of tool is especially used by scientists, while also being relevant for use by practitioners.

A fourth type of tool is **integrated assessment modeling**, including ecological food print analyses, cost-benefit analyses and target setting. These tools are indispensible for vertical integration, relating cause and effect to impact, and analyzing the responses by society (actors). The 'DPSIR model' is a conceptual tool for analyzing cause-effect relationships. It relates **D**riving forces of environmental change (population growth, economic growth, etc.), to **P**ressures on the environment (e.g., N_r emissions), to **S**tate of the environment (e.g., water quality), to **I**mpacts on population, economy and ecosystems, and finally to the **R**esponse of the society (OECD, 1991; EEA, 1995). Integrated assessment modelling is the interdisciplinary process that quantifies and analyzes these cause-effect relationships in the current situation (using empirical data and information) and for future conditions (using scenario analyses), in order to facilitate the framing of strategies. Examples include reviews of the Gothenburg Protocol by the Taskforce on Integrated Assessment Modelling of the UNECE Convention on Long-range Transboundary Air Pollution (TFIAM/CIAM, 2007). Cost-Benefit Analysis (CBA) go a step further by expressing costs and benefits of policy measures in monetary terms. However, attaching financial values to for example improvement of human health and increased ecosystem protection is not without its challenges (Brink et al., 2011). This type of tool is generally applied at the science-policy interface. They are also used to assess uncertainties in the cause-effect relationships and in the effects of management measures.

A fifth tool for integrated approaches to N management is '**logistics and chain management'**. This is the planning and management of activities, information and N sources in firms, installations and departments between the point of origin and the point of consumption. In essence, logistics and chain management integrate the supply and demand within and across companies. Logistics and chain management is especially important for N fertilizer producing companies, animal feed companies, transport and distribution sectors, processing industries, companies involved in recycling (sewage waste, composts, etc.), but also large farms. This type of tool is used especially by practitioners.

A sixth type of tool is **stakeholder dialogue**, including Multi Criteria Decision Analysis (MCDA), learning and participatory approaches. Evidently, this type of tool is indispensible for addressing the views of actors in N management issues (the 4th dimension of integration). The intention of stakeholder dialogue is to get people from different perspectives to enter a result-oriented conversation. Stakeholder dialogue is interaction between different stakeholders to address specific problems related to competing interests and competing views on how N and other resources should be used and managed. Rotmans (2003) describes the roles of stakeholders, networking, and self-governance in transition management. MCDA has been used in the water quality context and also in setting strategies for NH_3 control in a wider context (including dietary change). It is a good way of involving different stakeholder interests and for dealing with uncertainties.

Further, high-level meetings and resulting treaties are seen as a tool to achieve regional integration of N management measures. Regional integration is the most complex and encompassing way of integration. Also, there are many ways for and stages of regional integration, with not just one most superior outcome (in terms of ratification, exemptions, delayed implementation, etc.). This offers the opportunity of creating flexibility (Bull et al., 2011).

Finally, integrated approaches to N management can be expected to have different policy targets than policies oriented toward single N sources and N species. Based in part on the critical-load concept and emission ceilings for N species developed under the CLRTAP Gothenburg Protocol, it is suggested that incentive-based N budgets and N_r ceilings per area, sector and or activity could be useful indicators, because they integrate multiple elements of N effects in the environment (see also supplementary information to this chapter). The usefulness and analytical soundness of such indicators have to be further explored.

Elements of integrated nitrogen management

Management is often called the “fourth production factor”, in addition to land, labour and capital (techniques). Its importance for the economic and environmental performance of agricultural is enormous. Management is commonly defined as “a coherent set of activities to achieve objectives”. Nitrogen management can be defined as “a coherent set of activities related to the handling and allocation of N on farms to achieve agronomic and environmental/ecological objectives” (e.g., O. Oenema and Pietrzak, 2002). The agronomic objectives relate to crop yield and quality, and animal performance in the context of animal welfare. The environmental/ecological objectives relate to minimizing N losses from agriculture. “Taking account of the whole N cycle” emphasizes the need to consider all aspects of N cycling and all possible N lossses, to circumvent “pollution swapping”. Nitrogen management can be considered as the “software” and “org-ware”, while the techniques may be considered as the “hardware” of N emissions abatement. Hence, N management has to be considered in conjunction with the techniques used.

Depending on the type of farming systems, N management at farm level involves a series of management activities in an integrated way, including:

(a) Fertilization of crops;
(b) Crop growth, harvest and residue management;
(c) Growth of catch or cover crops;
(d) Grassland management;
(e) Soil cultivation, drainage and irrigation;
(f) Animal feeding;
(g) Herd management (including welfare considerations), including animal housing;
(h) Manure management, including manure storage and application;
(i) Ammonia emission abatement measures;
(j) Nitrate leaching and run-off abatement measures;
(k) N_2O emission abatement measures;
(l) Denitrification abatement measures.

To be able to achieve high crop and animal production with minimal N losses and other unintended environmental consequences, all activities have to be considered in an integrated and balanced way.

Nitrogen is often the most limiting nutrient, and therefore must be available in sufficient amount and in a plant-available form in soil to achieve optimum crop yields. Excess and/or untimely N applications are the main source of N losses to the environment. To avoid excess or untimely N applications is one of the best ways to minimize N losses, while not affecting crop and animal production. Guidelines for site-specific best nutrient management practices should be adhered to, including:

(a) Nutrient management planning and recordkeeping, for all essential nutrients;
(b) Calculation of the total N requirement by the crop on the basis of realistic estimates of yield goals, N content in the crop and N uptake efficiency by the crop;
(c) Estimation of the total N supply from indigenous sources, using accredited methods:
    (i) Mineral N in the upper soil layers at planting and in-crop stages (by soil and/or plant tests);
(ii) Mineralization of residues of the previous crops;

(iii) Net mineralization of soil organic matter, including the residual effects of livestock manures applied over several years and, on pastures, droppings from grazing animals;

(iv) Deposition of reactive N from the atmosphere;

(v) Biological N_2 fixation by leguminous plants;

(d) Computation of the needed N application, taking account of the N requirement of the crop and the supply by indigenous N sources;

(e) Calculation of the amount of nutrients in livestock manure applications that will become available for crop uptake. The application rate of manure will depend on:

(i) The demands for N, phosphorus and potassium by the crops;

(ii) The supply of N, phosphorus and potassium by the soil, based on soil tests;

(iii) The availability of livestock manure;

(iv) The immediately available N, phosphorus and potassium contents in the manure and;

(v) The rate of release of slowly available nutrients from the manure, including the residual effects;

(f) Estimation of the needed fertilizer N and other nutrients, taking account of the N requirement of the crop and the supply of N by indigenous sources and livestock manure;

(g) Application of livestock manure and/or N fertilizer shortly before the onset of rapid crop growth, using methods and techniques that prevent NH_3 emissions;

(h) Where appropriate, application of N fertilizer in multiple portions (split dressings) with in-crop testing, where appropriate.

The effectiveness of N management can be evaluated in terms of (a) decreases of Nsurplus; and (b) increases of N use efficiency. NUE indicators provide a measure for the amount of N that is retained in crop or animal products, relative to the amount of N applied or supplied. Nsurplus is an indicator for the N pressure of the farm on the wider environment, also depending on the pathway through which surplus N is lost, either as NH_3 volatilization, N leaching and/or nitrification/denitrification. Management has a large effect on both NUE (Tamminga 1996; Mosier, Syers and Freney, 2004) and Nsurplus.

While the ratio of total N output (via products exported from the farm) and total N input (imported into the farm, including via biological N_2 fixation) (mass/mass ratios) is an indicator for the NUE at farm level, the total N input minus the total N output (mass per unit surface area) is an indicator of the Nsurplus (or deficit) at farm level.

There are various procedures for making N input-output balances, including the gross N balance, the soil-surface balance, the farm-gate balance, and the farm balance (Watson and Atkinson, 1999; Schroder et al, 2003; Oenema et al, 2003; OECD, 2008). Basically, the gross N balance and the soil-surface balance record all N inputs to agricultural land and all N outputs in harvested crop products from agricultural land. However, the balances differ in the way they account for the N in animal manure; the gross N balance includes the total amount of N excreted as an N input item, while the soil-surface balance corrects the amount of N excreted for NH_3 losses from manure in housing systems and manure storage systems. The farm-gate balance and the farm balance records all N inputs and all N outputs of the farm; the farm balance includes N inputs via atmospheric deposition (both reduced and oxidized N compounds) and biological N_2 fixation. Various methods can be applied at the field, farm, regional and country levels; it is important to use standardized formats for making balances and to report on the methodology so as to improve comparability.

A farm N budget details all N inputs and outputs and including losses (figure 6). The main inputs are mineral/inorganic fertilizer, imported animal manure, fixation of atmospheric N_2 by some (mainly leguminous) crops, deposition from the atmosphere, inputs from irrigation water and livestock feed. Inputs in seed and bedding used for animals are generally minor inputs, although the latter can be significant for some traditional animal husbandry systems. The main outputs are in crop and animal products, and in exported manure. Gaseous losses occur from manure in animal housing, in manure storage and after field application. Other gaseous losses occur from fields; from applied fertilizer, crops, soil and crop residues. Losses to groundwater and surface water occur via leaching or run-off of nitrates, ammonium and DON. Run-off of undissolved organic N may also occur.

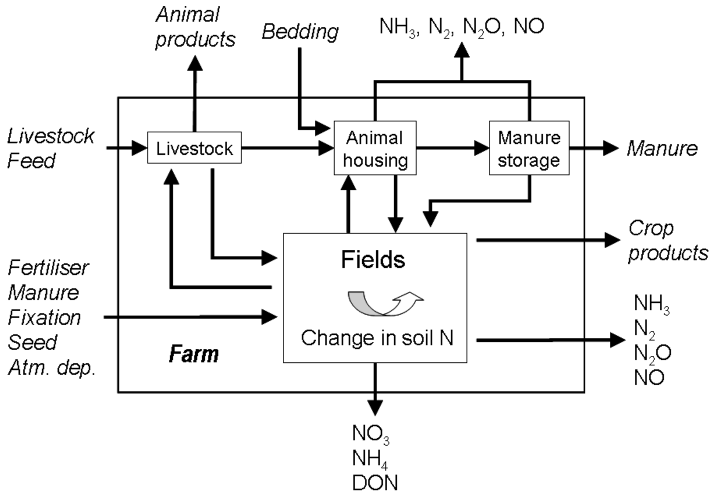

Figure 6. **A farm N budget of a mixed crop-animal production farm**
Source: Jarvis and others, 2011.

The farm N balance is simpler than a farm N budget, as the N losses are not detailed. The farm N balance details all N inputs and harvested N outputs (hence no N losses), as well as the balance, i.e., the difference between total N input and total N output.

A soil surface N balance of agricultural land is shown in figure 7. The main N inputs are mineral/inorganic fertilizer, animal manure, fixation of atmospheric N by leguminous crops, and deposition from the atmosphere. Other N inputs may include bio-solids, and organic amendments like compost and mulches. Inputs in seed and composts are generally minor inputs. The main outputs are in harvested crop products, which may be the grain or the whole crop. Note that animal products other than animal manure do not show up in the soil surface balance, as they are not placed onto the soil surface.

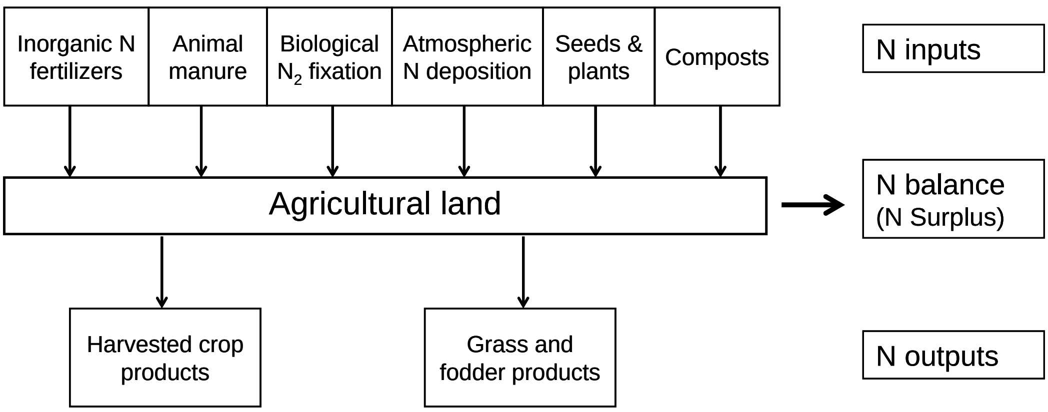

Figure 7. **Components of a soil surface N balance of agricultural land**
Source: OECD, 2008.

For using N balances and NUE as indicators at farm level, a distinction has to be made between:

(a) Specialized crop production farms;
(b) Mixed crop (feed)-animal production farms;
(c) Specialized animal production farms.

Specialized crop production farms have relatively few NH_3 emission sources (possibly imported animal manure, urea and ammonium-based fertilizers, crops and residues). These farms can be subdivided according to crop rotation (e.g., percentage of cereals, pulses, vegetables and root crops). Specialized animal production farms produce only animal products (milk, meat, egg, animal by-products and animal manure) and all these products are exported from the farm. Energy may also be produced through digestion of organic carbon. These farms can be subdivided according to animal categories (e.g., pig, poultry, and cattle). Mixed systems have both crops and animals; the crops produced are usually fed to the animals, while the manure produced by the animals is applied to the cropland. These farms can be subdivided according animal categories (e.g., dairy cattle, beef cattle, pigs, etc.) and livestock density (or feed self-sufficiency).

The variation between farms in NUE (output/input ratios) and Nsurpluses (input minus output) is large in practice, due to the differences in management and farming systems (especially as regards the types of crops and animals, the livestock density and the farming system). Indicative ranges can be given for broad categories of farming systems (see table 1).

Table 1 **Nsurplus and NUE indicators of farming systems, with typical values for specialized crop production farms, specialized animal production farms and mixed farms**

Index	*Calculation*	*Interpretation*	*Typical levels*
Nsurplus = sum of all N inputs minus the N outputs that pass the farm gate, expressed in kg/ha/yr	N surplus = Σ (Inputs$_N$) – Σ (outputs$_N$)	Nsurplus depends on the types of farming system, crops and animals, and indigenous N supply, external inputs (via fertilizers and animal feed) management and environment	Depends on types of farming systems, crops and animals:
		Nsurplus is a measure of the total N loss to the environment	Crop: 0–50 kg/ha
		N deficit [Σ (Inputs$_N$) < Σ (outputs$_N$)] is a measure of soil N depletion	Mixed: 0–200 kg/ha
		For specialized animal farming systems (landless), the Nsurplus can be very large, depending also on the possible N output via manure processing and export	Animal: 0–1,000 kg/ha
NUE = N use efficiency, i.e., the N output in useful products divided by the total N input	NUE = Σ (outputs$_N$) / Σ (Inputs$_N$)	NUE depends on types of farming system, crops and animals, and indigenous N supply, external inputs (via fertilizers and animal feed) management and environment	Depends on types of farming systems, crops and animals:
		For specialized animal farming systems (landless), there may be N output via manure export.	Crop 0.6–1.0 Mixed: 0.5–0.6 Animal 0.2–0.6[a] Animal 0.8–0.95[b]

[a] No manure export.
[b] Landless farms; all manure exported off-farm.

Nitrogen balances and N output-input ratios can be made also for compartments within a farm, especially within a mixed farming system. For estimating NUE, three useful compartments or levels can be considered:

(a) Feed N conversion into animal products (feed-NUE or animal-NUE);
(b) Manure and fertilizer N conversion into crops (manure/fertilizer-NUE);
(c) Whole-farm NUE.

These NUEs are calculated as the percentage mass of N output per mass of N input:

(a) Feed-NUE = [(N in milk, animals and eggs) / (N in feed and fodder)] x 100%;
(b) Manure/fertilizer-NUE = [N uptake by crops / N applied as manure/fertilizer] x 100%;
(c) Whole-farm NUE = [Σ(N exported off-farm) / Σ(N imported on to the farm)] x 100%.

Nitrogen management is based on the premise that decreasing the nitrogen surplus (Nsurplus) and increasing N use efficiency contributes to the mitigation of N losses via NH_3 emissions, nitrate leaching and denitrification. Nitrogen management also aims to identify and prevent pollution swapping between different N compounds and environmental compartments. Establishing an N input-output balance at the farm level is a prerequisite for optimizing N management in an integral way. Table 2 lists indicative ranges for N use efficiency (NUE) and the Nsurplus of the input-output balance of different farming systems. These ranges serve as rough guidance; they can be made more farm and country specific. Nitrogen use efficiency should be managed in concert with overall nutrient efficiencies and other factors, such as pest control.

Table 2. **Indicative ranges for target N surplus and NUE as a function of farming system, crop s**

Farming systems	***Species/ categories***	***NUE (kg/kg)***	***Nsurplus (kg/ha/yr)***	***Comments***
Specialized cropping systems	Arable crops	0.6–0.9	0–50	Cereals have high, root crops low, NUE
	Vegetables	0.4–0.8	50–100	Leafy vegetables have low NUE
	Fruits	0.6–0.9	0–50	
Grassland-based ruminant systems	Dairy cattle	0.3–0.5	100–150	High milk yield, high NUE; low stocking density, low Nsurplus
	Beef cattle	0.2–0.4	50–150	Veal production, high NUE; 2-year-old beef cattle, low NUE
	Sheep and goats	0.2–0.3	50–150	
Mixed crop-animal systems	Dairy cattle	0.4–0.6	50–150	High milk yield, high NUE; concentrate feeding, high NUE
	Beef cattle	0.3–0.5	50–150	
	Pigs	0.3–0.6	50–150	
	Poultry	0.3–0.6	50–150	
	Other animals	0.3–0.6	50–150	
Landless systems	Dairy cattle	0.8–0.9	n.a.[a]	N Output via milk, animals, manure + N-loss ~equals N input; Nsurplus is gaseous N losses from housing and storage
	Beef cattle	0.8–0.9	n.a.[a]	
	Pigs	0.7–0.9	n.a.[a]	
	Poultry	0.6–0.9	n.a.[a]	
	Other animals	0.7–0.9	n.a.[a]	

[a] Not applicable, as these farms have essentially no land. However, the Nsurplus can be expressed in kg per farm per year. In the case that all animal products, including animal manure and all residues and wastes, are exported, the target Nsurplus can be between 0 and 1,000 kg per farm per year, depending on farm size and gaseous N losses.

Measures to prevent and abate ammonia emissions

The Guidance document on preventing and abating ammonia emissions from agricultural sources lists 8 NH_3 emission abatement measures in the following areas:

(a) Nitrogen (N) management, taking into account the whole N cycle;
(b) Livestock feeding strategies;
(c) Animal housing techniques;
(d) Manure storage techniques;
(e) Manure application techniques;
(f) Fertilizer application techniques;
(g) Other measures related to agricultural N;
(h) Measures related to non-agricultural and stationary sources.

These measures are briefly summarized below.

Livestock feeding strategies decrease NH_3 emissions from manure in both housing and storage, and following application to land. Livestock feeding strategies are more difficult to apply to grazing animals, but emissions from pastures are low and grazing itself is essentially a category 1 measure.[1] Livestock feeding strategies are implemented through (a) phase feeding, (b) low-protein feeding, with or without supplementation of specific synthetic amino acids and ruminal by-pass protein, (c) increasing the non-starch polysaccharide content of the feed, and (d) supplementation of pH-lowering substances, such as benzoic acid. Phase feeding is an effective and economically attractive measure even if one that requires additional installations. Young animals and high-productive animals require more protein concentration than older, less-productive animals. Combined NH_3 emissions for all farm sources decrease roughly by 10% when mean protein content decreases by 10 grams (g) per kg (1%) in the diet. The economic cost of the livestock feeding strategies depends on the cost of the feed ingredients and the possibilities of adjusting these ingredients, based on availability, to optimal proportions. The reference here is the mean current practice, which varies considerably across countries and over time. The net costs of livestock feeding strategies depend on the manipulation of the diet and the changes in animal performance. In general, high-protein diets and efficient low-protein diets cost more than diets with medium-high protein contents. Both too high and too low protein contents in the diet have negative effects on animal performance, although the effects in the latter case are more evident to producers. The cost of the diet manipulations are in the range of -€10–€10 per 1,000 kg of feed, depending on market conditions for feed ingredients and the cost of the synthetic amino acids. Hence, in some years there are benefits while in other years there are costs associated with changes in diets. Table 3 summarizes possible targets for lowering protein values, maintaining production efficiencies for each animal category (see also annex II). Note that the economic costs increase as the ambitions to decrease the mean protein content increase from low to high.

[1] See paras. 18 and 19 for a description of the various categories.

Table 3 **Indicative target protein levels (%) of dry feed with a standard dry matter content of 88% for housed animals as function of animal category and for different ambition levels**

Animal type	*Mean crude protein content of the animal feed (%)*[a]		
	Low ambition	*Medium ambition*	*High ambition*
Cattle			
Dairy cattle, early lactation (> 30 kg/day)	17–18	16–17	15–16
Dairy cattle, early lactation (< 30 kg/day)	16–17	15–16	14–15
Dairy cattle, late lactation	15–16	14–15	12–14
Replacement cattle (young cattle)	14–16	13–14	12–13
Veal	20–22	19–20	17–19
Beef < 3 months	17–18	16–17	15–16
Beef > 6 months	14–15	13–14	12–13
Pigs			
Sows, gestation	15–16	14–15	13–14
Sows, lactation	17–18	16–17	15–16
Weaner, <10 kg	21–22	20–21	19–20
Piglet, 10–25 kg	19–20	18–19	17–18
Fattening pig, 25–50 kg	17–18	16–17	15–16
Fattening pig, 50–110 kg	15–16	14–15	13–14
Fattening pigs, >110 kg	13–14	12–13	11–12
Chickens			
Chicken, broilers, starter	22–23	21–22	20–21
Chicken, broilers, growers	21–22	20–21	19–20
Chicken, broilers, finishers	20–21	19–20	18–19
Chicken, layers, 18–40 weeks	17–18	16–17	15–16
Chicken, layers, > 40 weeks	16–17	15–16	14–15
Turkeys			
Turkeys, < 4 weeks	26–27	25–26	24–25
Turkeys, 5–8 weeks	24–25	23–24	22–23
Turkeys, 9–12 weeks	21–22	20–21	19–20
Turkeys, 13–16 weeks	18–19	17–18	16–17
Turkeys, > 16 weeks	16–17	15–16	14–15

For animal housing, abating NH_3 emissions is based on one or more of the following principles:

(a) Decreasing the surface area fouled by manure;
(b) Rapid removal of urine; rapid separation of faeces and urine;
(c) Decreasing the air velocity and temperature above the manure;
(d) Reducing the pH and temperature of the manure;
(e) Drying manure (especially poultry litter);
(f) Removing (scrubbing) NH_3 from exhaust air;
(g) Increasing grazing time.

Different animal categories require different housing systems and environmental conditions, hence different techniques. Because of their different requirements and housing, there are different provisions according to animal categories. The references used are the most conventional housing systems, without techniques for abating NH_3 emissions. The costs of techniques used to lower NH_3 emissions from housing are related to: (a) depreciation of investments; (b) economic rent on investments; (c) energy; and (d) operation and maintenance. In addition to costs, there are benefits related to increasing animal health and performance. These benefits are difficult to quantify and have not always been included in the total cost estimate. The economic costs vary because of different techniques/variants and farms sizes; techniques for cattle housing are still in development. Table 4 presents an overview of the emission reduction and economic cost for the major animal categories.

Table 4 **Ammonia emission reduction techniques for animal housing, their emission reduction levels and associated costs**

Category	*Emission reduction compared with the reference (%)* [a]	*Extra cost (€/kg NH_3-N reduced)*
Existing pig and poultry housing on farms with > 2,000 fattening pigs or > 750 sows or > 40,000 poultry	20	0–3
New or largely rebuilt cattle housing	0–70	1–20
New or largely rebuilt pig housing	20–90	1–20
New and largely rebuilt broiler housing	20–90	1–15
New and largely rebuilt layer housing	20–90	1–9
New and largely rebuilt animal housing on farms for animals other than those already listed in this table	0–90	1–20

For **manure storages**, abating NH_3 emissions is based on one or more of the following principles: (a) decreasing the surface area where emissions can take place, i.e., through covering of the storage, encouraging crusting and increasing the depth of storages; (b) decreasing the source strength of the emitting surface, i.e., through lowering the pH and ammonium (NH_4) concentration; and (c) minimizing disturbances such as aeration. All principles have been applied in category 1 (i.e., scientifically sound and practically proven) techniques. These principles are generally applicable to slurry storages and manure (dung) storage. However, the practical feasibility of implementing the principles are larger for slurry storages than for manure (dung) storages. The reference here is the uncovered slurry store without crust and uncovered solid manure heap.

The costs of techniques used to lower NH_3 emissions from storages are related to: (a) depreciation of investments; (b) economic rent on investments; and (c) maintenance. Here, a summary is provided of the total costs, in terms of euros per kg of ammonia-nitrogen (NH_3-N) saved (table S4). In addition to costs, there are benefits related to decreased odour emissions, decreased rainwater infiltration and increased safety (no open pits); some of these benefits are difficult to quantify and therefore have not been included here. Ranges of costs relate to different techniques/variants and farm size. Note that the cost of the storage system itself is not included in the cost estimates of table 5. Some covers can only be implemented when new storages are built. Manure processing, such as separation, composting and digestion, have implications for the total losses during "storage".

Table 5. **Ammonia emission reduction techniques for manure storages, their emission reduction levels and associated costs**

Techniques	*Emission reduction (%)*	*Cost (€ per m^3 per year)*	*Cost (€ per kg NH_3-N saved)*

Techniques	*Emission reduction (%)*	*Cost (€ per m³ per year)*	*Cost (€ per kg NH_3-N saved)*
Tight lid	> 80	2–4	1–2.5
Plastic cover	> 60	1.5–3	0.5–1.3
Floating cover	> 40	1.5–3*)	0.3–5[a]

[a] Not including crust; crusts form naturally on some manures and have no cost, but are difficult to predict.

Low-emission manure application is based on one or more of the following principles: (a) decreasing the surface area where emissions can take place, i.e., through band application, injection or incorporation; (b) decreasing the time that emissions can take place, i.e., through rapid incorporation of manure into the soil, immediate irrigation or rapid infiltration; and (c) decreasing the source strength of the emitting surface, i.e., through lowering the pH and NH_4 concentration of the manure (through dilution). All principles have been applied in category 1 (i.e., scientifically sound and practically proven) techniques. These principles are generally applicable to slurry and solid manure application. However, abatement techniques are more applicable and effective for slurry than for solid manures. For solid manure, the most feasible technique is rapid incorporation into the soil and immediate irrigation. The reference here is the broadcast spreading of slurry and solid manure. A fourth principle, applying when volatilization potential is low, such as under low temperature and wind conditions, is considered category 2 because it requires a method of validation. The costs of techniques used to lower NH_3 emissions from application are related to: (a) depreciation of investments costs of the applicator; (b)Economic rent on investments; (c) added tractor costs and labour; and (d) operation and maintenance.

Here, a summary is provided of the total costs, in terms of euros per kg NH_3-N saved (table 6). The co-benefits relate to decreased odour emissions and biodiversity loss, and increased palatability of herbage, uniformity of application and consistency of crop response to manure. Some of these benefits are difficult to quantify and therefore have not all been included in the cost estimations. Ranges of costs relate to the NH_4 content of the slurry/manure; the higher the NH_4 content, the lower the abatement cost. Mean costs are likely in the lower half of the range, especially when application is done by contractors, on large farms or with shared equipment.

Table 6. **Ammonia emission reduction techniques for manure application, their emission reduction levels and associated costs**

Manure type	*Application techniques*	*Emission reduction (%)*	*Cost (€ per kg NH_3-N saved)*
Slurry	Injection	> 60	-0.5–1.5
	Shallow injection	> 60	-0.5–1.5
	Trailing shoe,	> 30	-0.5–1.5
	Band application	> 30	-0.5–1.5
	Dilution	> 30	-0.5–1.0
	Management systems	> 30	0.0–2.0
	Direct incorporation following surface application	> 30	-0.5–2.0
Solid manure	Direct incorporation	> 30	-0.5–2.0

For **application of urea- and ammonium-based fertilizers**, abating emissions is based on one or more of the following principles: (a) decreasing the surface area where emissions can take place, i.e., through band application, injection, incorporation (but note that rapid increase in pH in concentrated bands of urea, especially where there is high crop residue, may lead to high emissions due to rise in pH); (b) decreasing the time that emissions can take place, i.e., through rapid incorporation of fertilizers into the soil or via irrigation; (c) decreasing the source strength of the emitting surface, i.e., through urease inhibitors, blending and acidifying substances; and (d) a ban on their use (as in the case of ammonium (bi)carbonate). All principles have been applied in category 1 (i.e., scientifically sound and practically proven) techniques. The reference here is the broadcast application of the urea- and ammonium-based fertilizers.

The costs of techniques used to lower NH_3 emissions from fertilizers are related to: (a) depreciation of investment costs of the applicator; (b) economic rent on investments; (c) use of heavier tractors and more labour time; and (c) maintenance. Here, a summary is provided of the total costs, in terms of euros per kg NH_3-N saved (table 7). The possible benefits relate to decreased fertilizer costs, decreased application costs in a combined seeding and fertilizing system and decreased biodiversity loss. These benefits are difficult to quantify and have not all been included. Ranges of costs relate to the farm size (economics of scale), soil conditions and climate (high emission reduction in relatively dry conditions). Mean costs are likely in the lower half of the range when application is done by contractors or low emitting fertilizers are substituted.

Table 7. **Ammonia emission reduction techniques for application of urea- and ammonium-based fertilizers, their emission reduction levels and associated costs**

Fertilizer type	*Application techniques*	*Emission reduction (%)*	*Cost (€ per kg NH_3-N saved)*
Urea	Injection	> 80	-0.5–1
	Urease inhibitors	> 30	-0.5–2
	Incorporation following surface application	> 50	-0.5–2
	Surface spreading with irrigation	> 40	-0.5–1
Ammonium carbonate	Ban	~100	-1–2
Ammonium-based fertilizers	Injection	> 80	0–4
	Incorporation following surface application	> 50	0–4
	Surface spreading with irrigation	> 40	0–4

Measures to decrease the risk of nitrate leaching losses

Water pollution within the context of the Nitrates Directive, has been defined as “the discharge, directly or indirectly of nitrogen compounds from agricultural sources into the aquatic environment, the results of which are such as to cause hazards to human health, harm to the living resources and to the aquatic ecosystems, damage to amenities or interference with other legitimate uses of water”. Further, eutrophication has been defined as “the enrichment of water by nitrogen compounds, causing accelerated growth of algae and higher forms of plant life to produce an undesirable disturbance to the balance of organisms present in the water and to the quality of the water concerned”. Though the emphasis is clearly on ‘nitrates from agricultural sources’ in the Nitrates Directive, it is noted that phosphorus is as well a dominant cause of eutrophication of many surface waters. Hence, phosphorus compounds from agricultural sources must be considered as well, when dealing with water pollution and eutrophication within the context of the Nitrates Directive. Moreover the Nitrates Directive forms integral part of the Water Framework Directive[2], which aims to reach good ecological status of waters. Particularly in intensive agricultural areas, high levels of P concentrations are one of the main obstacles to reach this goal.

Growing plants require relatively high concentrations of available N and P, and that is why farmers add N and P to soil, via animal manure, fertilisers, composts, residues and wastes. These additions of N and P can potentially pollute water. Pollution risks are determined by pedo-climatic conditions and farming practices. Risks are high when the availabilities of nitrogen (N) and phosphorus (P) are high under pedo-climatic conditions that are favourable to leaching and run-off. Conversely, risks are small when the availabilities of N and P are low and the pedo-climatic conditions are unfavourable to leaching. Vulnerability of water bodies is also an important factor to consider while assessing risk for water pollution due to leaching and run off of nutrients.

The actual vulnerability to leaching of a site depends on the pedo-climatic conditions and farming practices. As pedo-climatic conditions are largely defined by Mother Nature and are not easy to manipulate, to a certain extent they govern the available options for farming practices for ensuring environmental protection. Farming practices will hence have to be adjusted to the pedo-climatic conditions, when the objective is to decrease the risk of water pollution. Recommendations and regulations directed at the reduction of pollution risks should therefore ideally be tuned to these different situations. Farming practices refer to the intricate fabric of nutrient management (type and nature of fertilisers and manure, rate, timing and method of applications) in close connection with the complementary farm management (e.g. crop type choice, dates of sowing and harvest, drainage and irrigation, crop rotation, livestock feeding and housing). The above implies that regulations on any individual aspect should be defined in view of the many other aspects.

Article 5 of the Nitrates Directive requires Member States to establish Action Programmes, which should include measures aimed at preventing and reducing the risk of nitrate leaching and run off from agricultural practices. Action Programmes should include measures listed in Annex III of the Directive and those prescribed in the Code of Good Agricultural Practice, as listed in Annex II of the Directive, except where they are superseded by the measures of Annex III. The purpose of these measures is to minimize the risk of water pollution and to promote the use of ‘best farming practices’ (Box 3).

Box 3. Measures referred to in Annexes II and III of the Nitrates Directive
Annexes II and III of the Nitrates Directive set out a list of measures, which have to be included in the Code of Good Agricultural Practices (Annex II) and the Action Programme (Annex II and III). In particular, the Action Programmes must contain provisions relating to:
1. periods when the land application of certain types of fertilizer is prohibited or inappropriate;
2. the capacity and construction of storage vessels for livestock manures, including measures to prevent water pollution by run-off and seepage into the groundwater and surface water of liquids containing livestock manures and effluents from stored plant materials such as silage;;
3. the land application of fertilizer to steeply sloping ground;

[2] Directive 2000/60/EC

4. the amount of livestock manure applied to the land each year, including by the animals themselves, which shall not contain more than 170 kg N per hectare.
5. the land application of fertilizer to water-saturated, flooded, frozen or snow-covered ground;
6. the conditions for land application of fertilizer near water courses;
7. procedures for the land application, including rate and uniformity of spreading, of both chemical fertilizer and livestock manure, that will maintain nutrient losses to water at an acceptable level;
8. limitation of the land application of fertilizers, consistent with good agricultural practice and taking into account the characteristics of the vulnerable zone concerned, in particular: (a) soil conditions, soil type and slope; (b) climatic conditions, rainfall and irrigation; (c) land use and agricultural practices, including crop rotation systems; and to be based on a balance between: (i) the foreseeable nitrogen requirements of the crops, and (ii) the nitrogen supply to the crops from the soil and from fertilization corresponding to:
• the amount of nitrogen present in the soil at the moment when the crop starts to use it,
• the supply of nitrogen through the net mineralization of the reserves of organic nitrogen in the soil,
• additions of nitrogen compounds from livestock manure,
• additions of nitrogen compounds from chemical and other fertilizers.

Additional measures that can be taken are:
9 land use management, including the use of crop rotation systems and the proportion of the land area devoted to permanent crops relative to annual tillage crops;
10. the maintenance of a minimum quantity of vegetation cover during (rainy) periods that will take up the nitrogen from the soil that could otherwise cause nitrate pollution of water;
11. the establishment of fertilizer plans on a farm-by-farm basis and the keeping of records on fertilizer use;
12. the prevention of water pollution from run-off and the downward water movement beyond the reach of crop roots in irrigation systems

Pedo-climatic zones have specific ranges for crop growth potential, surface runoff risk potential and leaching risk potentials. Pedo-climatic zones are based on climate, landform and soil type characteristics. In this study, the pedo-climatic zones have been based on two separated layers of information. The first layer of information is the environmental stratification: the Environmental Zones (EnZs). The second layer of information deals with the surface run-off risk potential and nitrate leaching risk potential, based on a combination of landform, soil and climate factors (ie. pedo-climatic information). These two layers of information have been combined into two maps, showing the surface run-off risk potential and nitrate leaching risk potential for each ENZs, respectively.

Table 8. The 13 Environmental Zones (EnZs) as the first layer of information for pedo-climatic zonation in Europe.

Nr	Environmental Zone	Main locations and characteristics
1	Alpine North (ALN)	Scandinavian mountains; these have been named Alpine north, because they show environmental conditions as the Alps on a higher latitude, but in lower mountains.
2	Alpine South (ALS)	The high mountains of central and southern Europe that show the environmental conditions of high mountains. Also small Alpine patches are found in mountain areas in Pyrenees and Carpathians.
3	Atlantic North (ATN)	The area under influence of the Atlantic ocean and the North sea, humid with rather low temperatures in summer and winter, but not extremely cold.
4	Atlantic Central (ATC)	The area with moderate climate where the average winter temperature does not go far below 0°C and the average summer temperatures are relatively low. This is a main agricultural production zone in EU-27.
5	Boreal (BOR)	The environmental zone covering the lowlands of Scandinavia
6	Continental (CON)	The part of Europe with an environment of warm summers and rather cold winters. This is a main agricultural production zone in EU-27.

7	Lusitenean (LUS)	The southern Atlantic area from western France to Lisbon. Here, summers are rather warm and sometimes dry, while winters are mild and humid. This is a main agricultural production zone in EU-27.
8	Mediterranean North (MDN)	The Mediterranean north represents the major part of the Mediterranean climate zone with Cork Oak, fruit plantations and Olive groves
9	Mediterranean Mountains (MDM)	These mountains are influenced by both the Mediterranean and mountain climates.
10	Mediterranean South (MDS)	This zone represents the typical Mediterranean climate that is shared with northern Africa, short precipitation periods in winter and long hot, dry summers.
11	Nemoral (NEM	The zone covering the southern part of Scandinavia, the Baltic states and Belarus. This is a main agricultural production zone in EU-27.
12	Pannonian (PAN)	This is the most steppic part of Europe, with cold winters and dry hot summers. Most precipitation is found in spring.
13	Anatolian (ANA)	Represents the steppes of Turkey, a Mediterranean steppic environment.

Table 8 briefly describes the 13 distinguished EnZs. Figure 8 shows a map of the Environmental Zones (EnZs) in Europe. The map of the Environmental Zones (EnZs) has been combined with the map of the utilized agricultural area and with maps indicating the land, soil and climate factors that determine the surface runoff risk potential and the leaching risk potential. This combining has resulted in a pedo-climatic zoning that show the surface runoff risk potential (Figure 9) and the leaching risk potential (Figure 10) for utilized agricultural land within the Environmental Zones. Three classes have been distinguished for the surface runoff risk potential and the leaching risk potential: low, medium and high.

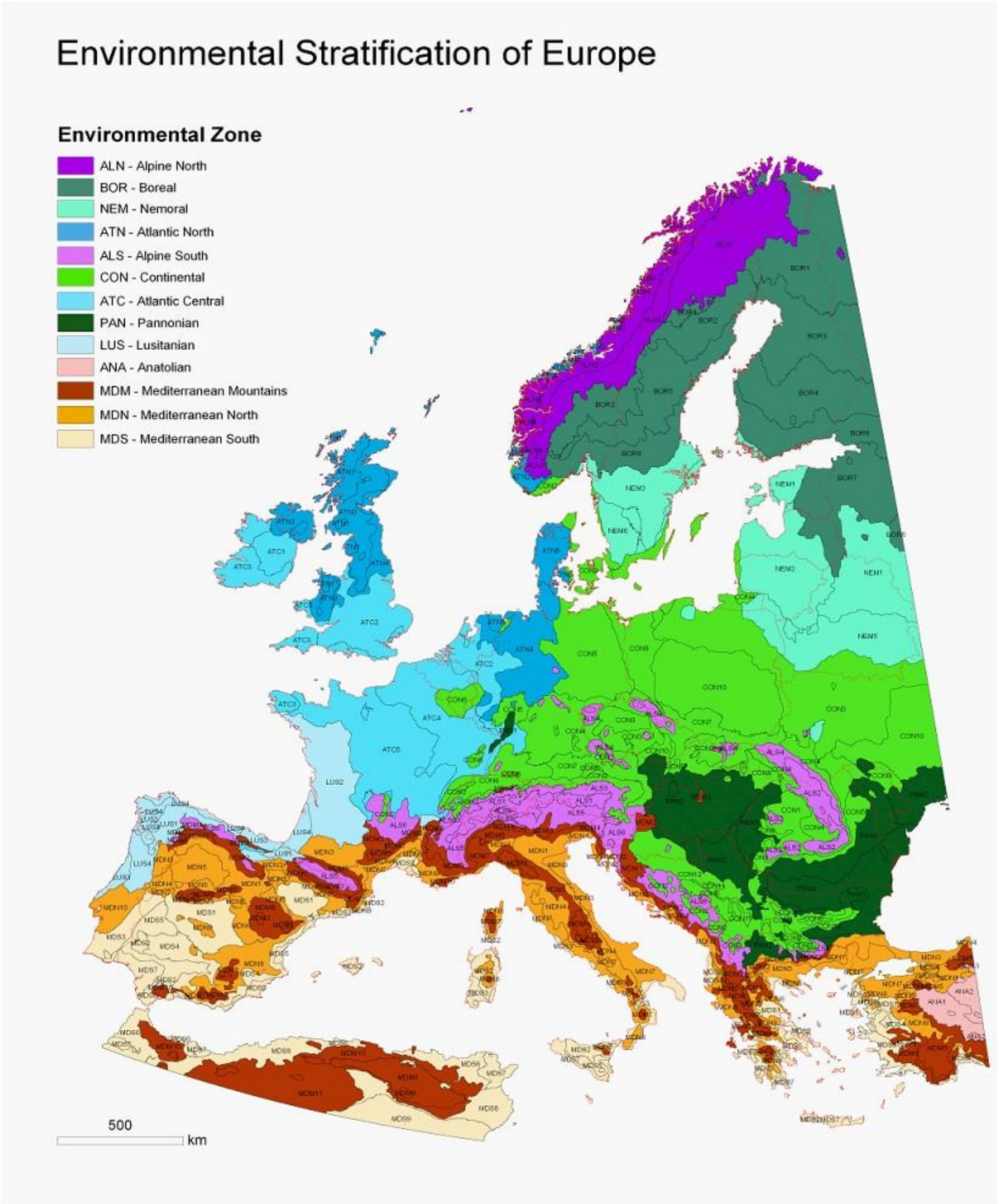

Figure 8. The Environmental Stratification of Europe.

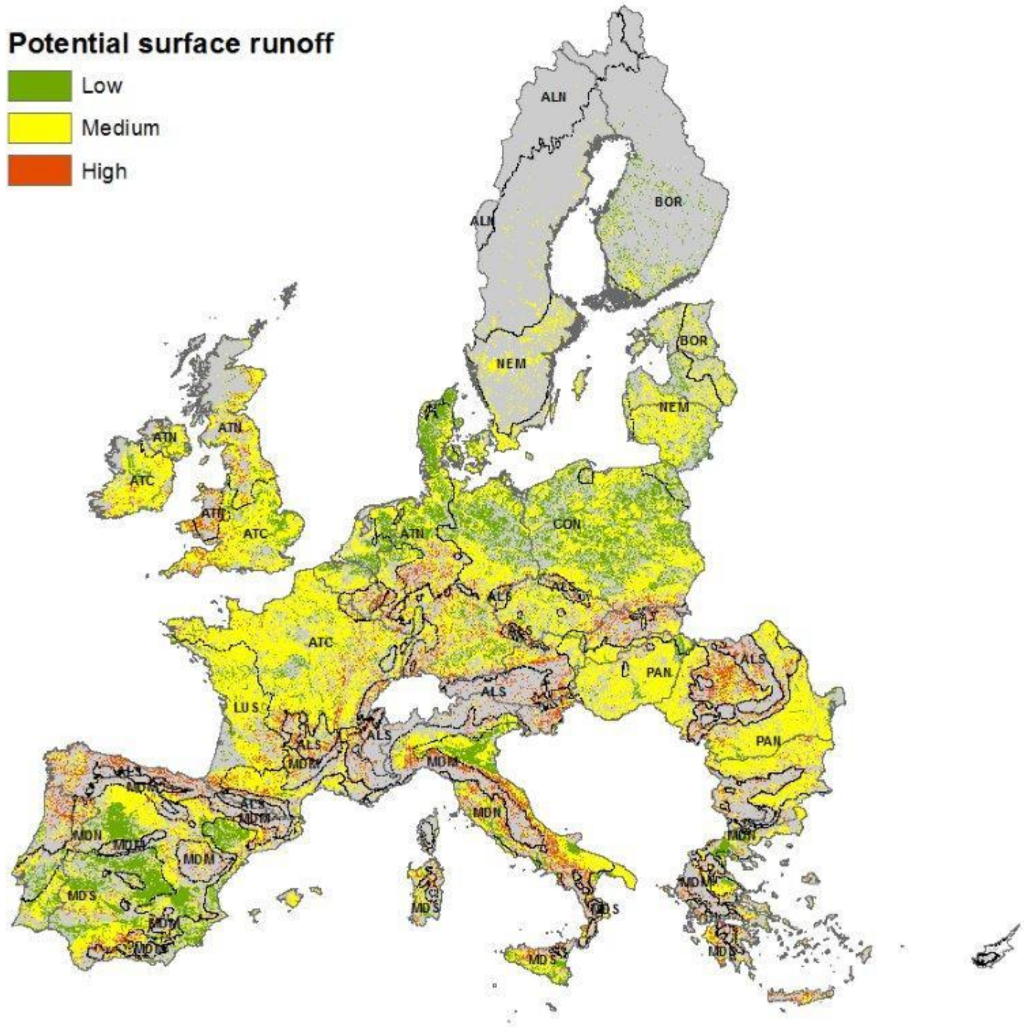

Figure 9. Map showing the surface runoff risk potential for agricultural land within the Environmental Zones in the EU-27. Abbreviations of the Environmental Zones are explained in Figure S1 and Table S1. Note that grey areas indicate non-agricultural areas.

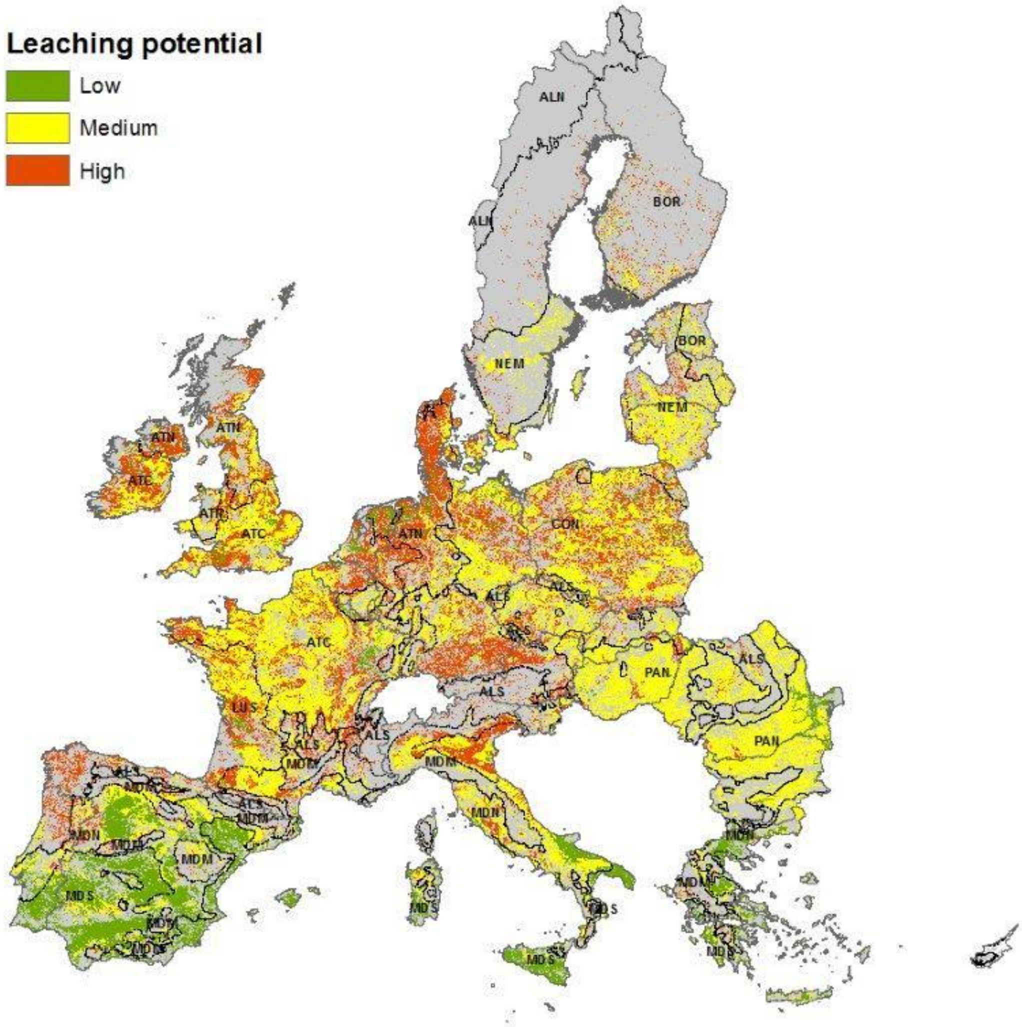

Figure 10. Map showing the leaching risk potential for agricultural land within the Environmental Zones in the EU-27. Abbreviations of the Environmental Zones are explained in Figure S1 and Table S1. Note that grey areas indicate non-agricultural areas.

Recommendations for measures have the character of a checklist, an encouraging instrument for making the measures of Annexes II and III of the Nitrates Directive site-specific and tailor-made. Evidently, this has to be done by the Member States in Action Programmes. Therefore, the recommendations presented in this report must be seen as just a first step.

Recommendations for measures of Annexes II and III of the Nitrates Directive have been linked to risks of surface runoff and leaching, whereby ‘risk’ has been perceived as consisting of (i) a frequency component (the incidence of occurrence), (ii) a mass component (mean loads), and (iii) a vulnerability component (some water bodies are more vulnerable to pollution and eutrophication than others). Risks are high when both the incidence of occurrence and the loads are high, and vulnerability of water bodies is high. Risks are also high when incidence of occurrence and loads are medium and vulnerability of receiving water body is high. Evidently, when risks are high, recommendations for measures must be stringent. Conversely, when the risks of surface runoff and leaching are low, the recommendations may be less stringent. However, the variability in weather conditions and the deleterious impact of nutrient leaching and runoff on groundwater pollution and eutrophication of surface waters will always necessitate ‘precautionary measures’.

Measures can be categorized according to the source-pathway-receptor concept, i.e. there are (i) source-based measures, (ii) pathway-based measures, and (iii) receptor or effects-based measures. Most of the measures of Annexes II and III of the Nitrates Directive are source-based and pathway-based measures. Examples of source-based measures are appropriated storage of animal manures and fertilizers, balanced fertilization, and prohibition periods for and restrictions on the application of manures and fertilizers. Examples of pathway-based measures are irrigation measures, drainage, buffer strips, green covers, terracing. Examples of receptor or effects-based measures are dredging and creation of riparian zones, etc.

The effectiveness of the measures depends on the site-specific adjustments of these general measures to the pedo-climatic conditions and farming practices. Hence, the ‘recommendations for measures’ basically are the site-specific or region-specific adjustments of the measures to the pedo-climatic conditions and farming practices, so as to increase their effectiveness. Recommendations for the implementation of all 12 measures of the Annexes II and III of the Nitrates Directive have been made specific and for all pedo-climatic zones in EU-27. The report also includes maps of the pedo-climatic zones for each Member State of the EU-27.

Example recommendations for measures

Periods when the land application of fertilizers and manures is inappropriate or prohibited.

Rationale and general recommendations:
Application of fertilizers and manures is inappropriate and prohibited when the demand of nutrients by the crop is low or when the risks for surface runoff and leaching of nutrients are high. Risks of nutrient leaching are most imminent when 1) the natural precipitation (including water liberated by thawing) exceeds the evapo-transpiration and the water holding capacity of the soil, 2) soils tend to crack which may lead to preferential flow, 3) soils contain considerable amounts of water-soluble N and P and 4) the ratio of mineral N to organically-bound N in applied manures, fertilizers and composts is high. Risks of overland flow, run-off and erosion are most imminent when 1) precipitation (including water liberated by thawing) exceeds the water infiltration rate into the soil, 2) the land is sloping, 3) the surface soil layers contain considerable amounts of water-soluble N and P. Note that the risk of runoff is not influenced by the ratio of mineral N to organically-bound N in applied manures, fertilizers and composts.

The part B report provides detailed information about the pedo-climatic factors influencing the prohibition period for pedo-climatic zones. General recommendations can be derived from the information presented in Table 9, however, farming practices and water vulnerability must be also considered.

Governing factors:
Pedo-climatic zones:
- Length of growing season
- Rainfall surplus outside growing season
- Temperature outside growing season
- Soil type and drainage
- Slope

Farming practices:
- Crop type and crop rotation
- Cover crops
- Type of manure
- Type of fertilizer

Vulnerability of water bodies
- Ecological and chemical status
- Travel time of N and P from nearby sources to the water bodies

Table 9. Ranking of precipitation surpluses per month per environmental zone (green=evapotranspiration exceeding rainfall in arable crops and on grassland, yellow=evapotranspiration exceeding rainfall on grassland, red=rainfall exceeding evapotranspiration on both arable crops and grassland; LT = months with average lowest temperature below 0 °C, LP = months with precipitation surplus exceeding a value of minus 150 mm).

ENZs	Month:											
	Jan	Feb	March	April	May	June	July	August	Sept	Oct	Nov	Dec
ALN	**LT**	**LT**	**LT**	**LT**	**(LT)**					**LT**	**LT**	**LT**
ATN	**LT**	**LT**										
ALS	**LT**	**LT**	**LT**								**LT**	**LT**
BOR	**LT**	**LT**	**LT**	**(LT)**						**LT**	**LT**	**LT**
LUS						**LP**						
NEM	**LT**	**LT**	**LT**								**LT**	**LT**
ATC												
MDM	**LT**					**LP**						
MDN						**LP**	**LP**					
CON	**LT**	**LT**	**(LT)**									**LT**
PAN	**LT**	**LT**										**LT**
ANA						**LP**	**LP**					
MDS						**LP**	**LP**	**LP**				

The capacity and construction of storage vessels for livestock manure.

Rationale and general recommendations:

The capacity of storage vessels for livestock manure must be large enough to store the manures produced during the period when the application of manures is prohibited, plus the amounts produced during a so-called pre-cautionary period. The latter period accounts for incidental weather extremes, and/or farm management failures, which necessitate a longer storage duration. Also, the larger the storage vessel, the more application can be adjusted to the time crops need nutrients (leading to increased manure efficiency). The construction of the storage vessel must be robust and leak-tight and should be covered preferably to minimize the loss of gaseous ammonia and the influx of rainwater. The amount of excreted manure in terms of volume is closely related to the amount of manure in terms of excreted N and P. As N and P excretion are a function of production level, live weight, feed conversion (and feed 'digestibility') and the N and P contents of feedstuffs, the excreted volumes depend on these factors too. Excretion can be manipulated by manipulating the feed composition and drinking water supply, by tuning the daily ration of individual animals to their actual production level, and by the use of for example artificial enzymes (phythase) and amino acids. The part B report provides detailed information about the assessment of the storage capacity, as function of animal species and pedo-climatic zone. General recommendations can be derived from the information presented in Table 10.

Governing factors :

Pedo-climatic zones:

- Length of the period when the land application of manure is inappropriate/prohibited + precautionary period (see above)

Farming practices:

- Number and type of animal species
- Manure production per animal species
- Manure type: solid, liquids and slurries
- Addition of bedding material and litter
- Addition of cleaning, spilling and rain waters
- Bottom sealing
- Presence of storage cover
- Manure processing and transport
- Evaporative losses and decomposition losses

Vulnerability of water bodies

- Ecological and chemical status
- Travel time of N and P from nearby sources to the water bodies

Table 10. Minimum manure storage capacity (months of manure production) per environmental zone (ENZ) based on the probability of a precipitation surplus, periods of drought and frost and unforeseeable weather extremes

Nr	ENZs	Type of crops grown	
		100% Arable	100% Grassland
1	ALN – alpine north	>10	>9
2	ALS – alpine south	>9	>6
3	ATN – Atlantic north	>8	>7
4	ATC – Atlantic central	>7	>3
5	BOR – boreal	>8	>7
6	CON – continental	>7	>4
7	LUS – Lusitanian	>8	>4
8	MDN – Mediterranean north	>5	>2
9	MDM – Mediterranean mountains	>8	>3
10	MDS – Mediterranean South	>3	>3
11	NEM – Nemoral	>7	>5
12	PAN – Pannonian	>6	>3
13	ANA – Anatolian	>6	>2

Limitation of the land application of fertilizers.

Rationale and general recommendations:

The application rate of fertilizer N has to be based on a balance between the foreseeable N requirements of the crops, and the N supply to the crops from the soil and other sources, including the amount of available N in the soil at the moment when the crop starts to use it, the supply of available N through atmospheric deposition, irrigation water, biological fixation and the net mineralization of organic N in the soil during the growing season, the supply of available N through livestock manures, composts, residues, wastes and/or any fertilizer. If too much manure or fertiliser is applied i.e. more than what is needed by crops, the excess nutrients will to a very limited extent be taken up as luxury consumption. Most of it will accumulate in the soil and sooner or later will be lost to the environment. Consequently, water protection requires limitation of fertiliser applications, on the basis of crop requirements. Depending on the vulnerability of the receiving water body and its quality status, lower applications could be needed in view of water protection.