Principles of integrated, sustainable nitrogen management

*Draft section for a Guidance Document*

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For discussion at the workshop on integrated sustainable nitrogen management,

Brussels 30 September – 1 October 2019
This draft chapter to a planned Guidance Document on integrated sustainable nitrogen management has been prepared for the Task Force on Reactive Nitrogen under the UNECE Air Convention, with support from the European Commission. The process of drafting the Guidance Document started in connection to a workshop “Towards joined-up nitrogen guidance for air, water and climate co-benefits”, hosted in Brussels, 11-12 October 2016. The current chapter draft is based on the results from that workshop and on discussions and developments since then. It will be presented and discussed in Brussels on 30 September – 1 October at a second workshop jointly organised by the Task Force on Reactive Nitrogen and the European Commission.

The content of the draft paper reflects the views only of the authors and the European Commission cannot be held responsible for any use which may be made of the information.
Principles of integrated, sustainable nitrogen management

1. Introduction and background
The purpose of this document is to outline principles of sustainable nitrogen (N) management in agriculture. These principles should form the basis for policy measures and best N management practices aimed at achieving (i) high N use efficiency in agriculture and (ii) acceptable low N losses from agricultural systems to the environment, taking an integrated approach to impacts on air, water, soil and climate.

Nitrogen management has a dual purpose in society. One purpose is to optimize the beneficial effects related to especially food production. The other purpose is to decrease the negative effects of excess nitrogen, especially on human health and biodiversity. Depending on local situation and the stakeholder(s) involved, the emphasis is either on the first or the second purpose or both. This chapter reflects this duality.

The chapter starts with a section on the principles (characteristics) of N cycling in the biosphere, to inform the reader about the nature of the N cycle. The second sections discusses principles of N management in agriculture. The third section discusses the possible dimensions of integrated N management in food systems. Based on these principles and dimensions, the fourth section then presents tools for integrated N management, from a policy perspective.

2. Principles of nitrogen cycling

1. Nitrogen is essential for life. It is an element of chlorophyll in plants and of amino acids (protein), nucleic acids and adenosine triphosphate (ATP) in plants, animals and humans.

2. Excess nitrogen has a range of negative effects, especially on human health and biodiversity, and it has various impacts on climate change. The total amounts of nitrogen introduced into the global biosphere by human activities have significantly increased during the last century, and have now exceeded critical limits for the so-called "safe operating space for humanity" (Steffen et al., 2015). The deleterious effects of excess nitrogen on human health and biodiversity are most apparent in regions with intensive agriculture, especially intensive animal husbandry, urban areas, and in large rivers and nearby coastal areas.

3. Nitrogen exists in various forms; it is transformed from one form in another through biochemical processes, mediated by micro-organisms, plants and or animals, and through chemical processes, mediated by increased temperature and pressure, and possible catalysts. This has a number of implications:

   - Most nitrogen forms are ‘reactive’, because these forms are easily transformed in the biosphere into another form through biological, photochemical and radiative processes. Reactive nitrogen includes (i) inorganic reduced forms (e.g. ammonia (NH₃) and ammonium (NH₄⁺), (ii) inorganic oxidized forms (e.g. nitrogen oxide (NO, NO₂)), nitric acid (HNO₃), nitrous oxide (N₂O), nitrite (NO₂⁻) and nitrate (NO₃⁻), and (iii) organic reduced forms (e.g. urea, amines, proteins and nucleic acids). Reduced forms are energy donor, proton donor, and electron acceptor. Oxidized forms are proton acceptor and electron donor. Although a reduced form, di-nitrogen (N₂) is not a reactive N form, because a
lot of energy (and a catalyst) is needed to break the bonding between the two N atoms.

- **Nitrogen is ‘double mobile’,** because some forms are gaseous and easily transported via air (e.g., di-nitrogen (N$_2$), nitrous oxide (N$_2$O), nitrogen oxide (NO, NO$_2$), ammonia (NH$_3$), and other forms are soluble in water and easily transported as solutes (e.g., nitrate (NO$_3^-$), ammonium (NH$_4^+$), urea (CO(NH$_2$)$_2$), dissolved organic nitrogen (DON)).

- Essentially all reactive N forms, including proteins, are toxic to humans and animals (and plants), when exposed to high concentrations. The toxic concentration levels greatly differ between forms.

- In summary, the reactivity, mobility, functions (and toxicity) of the various nitrogen forms in the biosphere differ greatly.

4. Most of the nitrogen in plants is taken from soil via roots, in the form of nitrate (NO$_3^-$) or ammonium (NH$_4^+$). The N uptake depends on the N demand by the crop, the root length density, and the concentrations of nitrate (NO$_3^-$) and ammonium (NH$_4^+$) in the soil solution. The N demand by the crop depends on crop type and variety, leaf area index (LAI) and climate. The uptake rate of N in plants commonly follows Michaelis–Menten kinetics, which implies that a maximum rate is achieved at a saturating substrate (NO$_3^-$, NH$_4^+$) concentration. Both, the demand of N by the crop and the supply of N via the soil depend on various processes, which are influenced by weather conditions and management. Dominant sources of NO$_3^-$ and NH$_4^+$ in soil are (i) mineralization of organically bound nitrogen in soil, (ii) inputs via animal manure, compost and wastes, (iii) input via synthetic N fertilizers, (iv) inputs via atmospheric deposition, and (v) inputs via biological N$_2$ fixation in soil and plant roots.

5. Some crop types are able to convert non-reactive di-nitrogen (N$_2$) from air into reactive N forms (amine, protein) in the plant roots. Important crops include the legume family (Fabaceae or Leguminosae) with taxa such as (soy)beans, peas, alfalfa, clover, and lupins. They contain symbiotic bacteria called Rhizobia within nodules in their root systems, which are able to convert N$_2$ into amine. The N$_2$ fixation rate depends on the availability of NO$_3^-$ and NH$_4^+$ in soil; the rate is low when the availability of NO$_3^-$ and NH$_4^+$ in soil is high, and vice versa. Biological N fixation (BNF) is an important source of reactive N in the biosphere (and agriculture).

6. Most of the protein-N needed by animals is ingested as protein via feed, and that by humans via food. The protein-N need (or amino acid requirements) of animals mainly depend on animal category, body weight, growth rate, milk and egg production, activity (labour, grazing) and reproduction. The protein-N need (or amino acid requirements) of humans mainly depend on body weight, growth rate, activity, and reproduction. Only a fraction of the N in food and feed is retained in body weight and/or milk and egg; the remainder is excreted via urine and faeces (in the forms of urea, ureic acid and ammonia). The N retention rate is strongly dependent on animal breed, feed quality, age and herd management, and commonly ranges from 5 to 15% in beef production, 15 to 30% in dairy production, 25 to 40% in pork production, and from 40 to 50% in poultry production. The remainder is in animal manure, commonly half in the form of ammonium (NH$_4^+$) and half in organically-bound form. The ammonium (NH$_4^+$) is conducive to N losses via volatilization of ammonia (NH$_3$), and leaching, but depending on storage conditions and environmental conditions.

7. **Nitrogen cycles** from soil to plants and animals to air to water bodies, and back again, and from one region to the other, as a results of natural driving forces and human activities. The natural primary forces are (i) solar energy, (ii) gravitation energy, (iii) internal particle energy,
and (iv) earth core energy. These primary forces fuel natural secondary driving forces, which all influence nutrient transport in the biosphere (Fig. 1). These natural driving forces of the N cycle have to be understood for effective N management.

Figure 1. Driving forces of nitrogen transformations and transport in natural systems. There are four primary energy sources (first column), which fuel the secondary driving forces and subsequently the nutrient transformation and transport processes in nature (Source: Liu et al. in press).

8. Human activities have greatly altered the natural N cycle. Human activities have fuelled a range of processes, including land-use change, food production, fertilizer production, breeding, irrigation, and fossil fuel combustion, which all affect N cycling. Urbanization and the globalization of food systems have increased the transport of food and feed across the world, including the transport of N embedded in the food and feed. Urbanization and the globalization of food systems have led to increased N depletion where the food and feed has been produced (in rural areas) and to increased N enrichment where the food and feed are being utilized (in urban areas and in areas with high livestock density). This spatial segregation of food and feed production from food and feed consumption challenge the establishment of a circular economy approach and efficient N recycling at whole food system level. The spatial segregation of food and feed production and consumption is also one of the key factors why N use efficiency at whole food system level has decreased in the world during the last decades.

3. Principles of nitrogen management in agriculture

1. The purpose of management is to achieve objectives. The purpose of N management in agriculture is to increase crop and animal productivity and N use efficiency, and to decrease N losses to agreed (acceptable) levels, thereby avoiding pollution of air and water.
2. There are various actors in agriculture, and all have a role in N management, but differently (in theory complementary, but not necessarily). These actors include (i) suppliers of fertilisers, feed, germplasm, machinery and loans, (ii) advisors, extension services, accountancy specialists, financial organisations, (iii) farmers, (iv) processing industries (crop products, dairy, meat, etc.), (v) retail organisations, and (vi) consumers. Evidently, farmers have a main role to play in N management, also in decreasing N losses. Thereby, farmers bear the burden of the economic cost of measures needed to decrease N losses. These cost are difficult to transfer to (spread over) other actors in food production – consumption chain, because farmers have little or no ‘market power’ in a globalized food system. This is one of the reason for the relative reluctance of farmers to implement costly measures to reduce N losses, because they may lose competitiveness relative to farmers that do not implement measures. At the same time, farmers feel the pressure from consumers’ behaviour and retail organisations to offer cheap food. This creates a downward trend on real prices of agricultural products and incentives on farmers to further lower cost per unit of produce. This has implications for N management, because measures will have to be cheap and easy to implement for enabling farmers to implement measures easily.

3. The dominant N loss pathways in agriculture are (i) ammonia volatilization, (ii) downward leaching of (mainly) nitrate to groundwater and then to surface waters, (iii) overland flow and erosion of basically all N forms to surface waters, and (iv) nitrification-denitrification processes combined with the gaseous emissions of nitrogen oxides (NO, NO₂), nitrous oxide (N₂O) and di-nitrogen (N₂). These pathways are strongly influenced by the availability and form of N sources, climate, soil and geomorphological/hydrological conditions and management. Pathway-specific measures are required to decrease pathway-specific N losses, but N input control influences all N loss pathways.

4. Reducing one form of nitrogen pollution has the risk of increasing other forms of nitrogen pollution, sometimes termed ‘pollution swapping’. A fundamental principle to avoid this is to recognize that a measure to reduce one form of pollution leaves more nitrogen available in the farming system, so that more is available to meet crop and animal needs. In order to realise the benefit of a measure to reduce N pollution (and to avoid pollution swapping), this needs to be matched by either reduced N inputs or increased N in harvested outputs. Reduced N inputs or increased harvested outputs are thus an essential part of integrated nitrogen management while providing opportunity for increased economic performance.

5. The N input-output balance is a main indicator of N management. It follows from the law of mass conservation: ‘what gets in, must get out’, i.e., N input = N output in harvested products – N losses (Fig. 2). It illustrates that N input control is a main mechanism to reduce N losses.
6. Matching nitrogen inputs to crop-needs and to livestock-needs offers opportunities to reduce all forms of nitrogen losses, and helps to improve the economic performance at the same time. In addition, increasing partial factor productivity (increase the output, without additional N input) increases N use efficiency and reduces all forms of N losses. This follows directly from the aforementioned law of mass conservation.

7. Crop yield, N uptake and N use efficiency depend on (i) yield defining factors (crop type and variety, climate), (ii) yield limiting factors (availability of all 14 essential nutrient elements and water, and soil quality), and (iii) yield reducing factors (competition by weeds, incidence of pest and diseases, occurrence of high soluble salt and/or toxic compounds in soil, and air pollution (e.g., ozone)). According to the law of the optimum, the yield-enhancing effect of nitrogen is largest when all yield defining factors are at optimal levels, and yield limiting and reducing factors are nullified. As a result, maximizing nitrogen use efficiency in crop production requires an integrated approach; a whole suit of management measures, i.e., (i) selecting high-yield crop varieties, adapted to the local climatic and environmental conditions, (ii) preparing a seedbed as function of crop seed type prior seeding/planting, and providing adequate levels of all essential nutrient elements (possibly through fertilization) and water (possibly through irrigation), and (iii) proper weed control, pest and disease management, and pollution control.

8. Animal production and N retention in animal products also depend on (i) yield defining factors (animal species and breed, climate), (ii) production limiting factors (feed quality, availability of all 22 essential nutrient elements and water), and (iii) production reducing factors (diseases, fertility, toxicity, air pollution (e.g., ammonia, H₂S, ozone)). Again, according to the law of the optimum, the yield-enhancing effect of protein-N feeding is
largest when all yield defining factors are at optimal levels, and yield limiting and reducing factors are nullified. As a result, maximizing nitrogen use efficiency in animal production requires an integrated approach; a whole suit of management measures, i.e., (i) selecting high-yield animal species and breeds, adapted to the local climatic and environmental conditions, (ii) availability of high quality feed and water, good feeding management and herd management, and (iii) proper disease, health, fertility and pollution control. All these animal crop husbandry measures are conducive to high animal productivity, N retention in animal products and high N use efficiency.

9. Minimizing exposure of ammonium-rich resources to the air is fundamental to reducing ammonia emissions. Hence, reducing the surface area and covering ammonium-rich resources reduces ammonia emissions. Lowering the pH (to ≤6.5) of the ammonium-rich resources also lowers ammonia emissions. Lowering temperature of ammonium-rich resources and the wind speed above the surface also reduces ammonia emissions.

10. Ammonium (NH₄⁺) in soil is less mobile and less vulnerable to losses via leaching and nitrification-denitrification processes than nitrate (NO₃⁻), the other dominant N form in soil utilized by crops. Therefore, promoting conditions that slow down nitrification (the biological oxidation of NH₄⁺ to NO₃⁻) will contribute to increasing nitrogen use efficiency and overall reduction of nitrogen losses. Synthetic nitrification inhibitors and biological nitrification inhibitors (BNIs) exuded by plant roots (Coskun et al., 2017. Nature Plants) slow down nitrification and help conserve N in the system and thereby may increase N use efficiency (Lam et al., 2016).

11. Nitrogen losses from agriculture via the greenhouse gas nitrous oxide (N₂O) represents a relatively small losses, while the associated N₂ loss via nitrification-denitrification represents a much larger loss of N resources. Hence, strategies aimed at reducing N₂O emissions reduce N₂ losses too, and save nitrogen resources at the same time.

12. Interactions between nitrogen and phosphorus affect the nitrogen and phosphorus use efficiencies in crop and animal production as well as their impacts on the eutrophication of surface waters. A suboptimal availability of phosphorus (and other essential nutrients) limits the uptake and utilization of nitrogen in crop and animal production, and limits eutrophication effects of nitrogen in surface waters. Conversely, a suboptimal availability of nitrogen limits the uptake and utilization of phosphorus in crop and animal production, and limits the eutrophication effects of phosphorus in surface waters. However, over-optimal availability of nitrogen and phosphorus decreases both nitrogen and phosphorus use efficiencies, greatly increases the risk of both nitrogen and phosphorus losses, and exaggerate the eutrophication effects in surface waters. Further, total losses of both nitrogen and phosphorus exceed ‘planetary boundaries’, which indicates that both nitrogen and phosphorus losses have to decrease greatly. This underlines the need for an integrated approach in which the availability of both nitrogen and phosphorus in agriculture and surface waters have to be considered jointly.

13. Interactions between nitrogen and water affect the nitrogen and water use efficiencies in crop production as well as affect the nitrogen loss pathways. A suboptimal availability of water limits the uptake and utilization of nitrogen in crop production, and limits nitrogen leaching and denitrification losses; it may lead to accumulation of nitrate-
nitrogen in soil. Rainfall and sprinkler irrigation greatly reduce nitrogen losses via ammonia volatilization from urea fertilizers and manures applied to land. Conversely, a suboptimal availability of nitrogen limits water use efficiency in crop production. However, an over-optimal availability of nitrogen and water decreases both nitrogen and water use efficiencies, and greatly increases the risk of nitrogen losses via leaching, erosion and denitrification. Application of targeted amounts of water and nitrogen through drip irrigation (fertigation) has the potential to greatly increase nitrogen and water use efficiencies simultaneously, and to minimize nitrogen losses. Further, crop yields at global scale are mostly limited by the availability of both water and nitrogen (Mueller et al., 2012). This underlines the need for an integrated approach in which the availability of both nitrogen and water are considered jointly, especially in those regions of the world where food production is limited by the availability of both water and nitrogen, and where food production has to increase to meet the demands of the growing human population.

14. Protein-rich diets are conducive to a relatively high nitrogen excretion, which have a high potential for ammonia volatilization losses. Conversely, low-protein diets are conducive to a relatively low nitrogen excretion, which have a low potential for ammonia volatilization losses. However, low-protein diets commonly have low fibre content, which is conducive to enteric methane production in ruminants. Methane is a potent greenhouse gas and ruminants are one of the main sources of methane emissions to the atmosphere in the world. Evidently, the target is to find the optimal protein level in the diet of ruminants, so as to minimize both ammonia losses and methane emissions.

15. The carbon-to-nitrogen ratio in organic matter in soil roughly ranges from 10 to 15 (with extreme values up to more than 30 in organic soils). This rather fixed ratio has a number of implications. First, carbon sequestration in soil aimed at reducing carbon dioxide (CO2) emissions to the atmosphere and improving soil quality, is associated with nitrogen sequestration in soil. Second, achieving the objectives of the ‘4 per 1000’ initiative (four per mil; https://www.4p1000.org) leads to a massive storage of nitrogen in soil, an amount which is nearly equivalent to the current global N fertilizer production annually. Third, storing organic carbon in soil means that the organic carbon first has to be produced, which requires crop production levels far beyond the current and projected crop production levels. These yield levels are associated levels where the ‘law of diminishing returns’ holds, in terms of nitrogen use efficiency. These possible trade-offs should not be neglected.

16. A circular economy aims at reducing wastes and the continual re-use of resources. Many principles of the management of ‘circular systems’ apply also to the principles of sustainable N management, including the principles of (i) reduce losses, (ii) reduce, reuse and recycle wastes, (iii) realign and reduce inputs, (iv) reduce excessive consumption, and (v) change systems so as to make them leak-tight and resilient. However, the nature of the (leaky) N cycle, and the effects of urbanization and of the globalization of our food systems challenges achieving circular systems with minimal losses.
4. Dimensions of integrated nitrogen management

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 about integrated nitrogen management is in part confused by lack of clear and accepted definitions about the term ‘integrated’. Integration is perceived as combining separate elements and aspects in an organized way, so that the constituent units function cooperatively. 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. These dimensions are discussed further below.

4.1. Vertical Integration

Vertical integration in N management 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 EEA, 1995; OECD, 1991) and the ‘effects-based approach’ to emissions abatement policies as applied in the Gothenburg Protocol (UNECE, 1991). 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 biodiversity, although significant progress has been made (ten Brink et al., 1991). Evidently, including cost-benefit analyses would make vertical integration of N management more complete.

4.2. 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 NOx sources and all NH3 sources have been included, but N2O 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 NO3 leaching to waters, but NH3 and N2O emissions to air are not addressed explicitly). Similarly, the emission of gaseous N2 through denitrification is not considered in any of these policies. Although emission of gaseous N2 does not lead directly to adverse environmental effects, its release can be considered as a waste of the energy used to produce N2, indicating the need that N2 emissions should also be addressed.

Conceptually, the N cascade model (Erisman et al., 2011; Galloway et al., 2003) 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.
4.3. Integration of other Elementes and Compounds

Emissions of NO\textsubscript{x}, NH\textsubscript{3} and sulphur dioxide (SO\textsubscript{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 both NO\textsubscript{x}, NH\textsubscript{3} and SO\textsubscript{2}. Similarly, emissions of N\textsubscript{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 (e.g. in the Water Framework Directive). 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\textsubscript{2}, CH\textsubscript{4} and N\textsubscript{2}O to the atmosphere. Climate change policies address these greenhouse gases simultaneously. Nitrogen may also affect CO\textsubscript{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 are large. From the practitioner point of view, there can be benefits when managing N and specific other elements simultaneously. This holds for example for NO\textsubscript{x} and SO\textsubscript{2} (and soot) from combustion sources, and N and P in agriculture and in sewage waste treatment.

4.4. 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. 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 (Tuinstra et al. 2006). 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 (EU, 2000), 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.

4.5. Regional Integration

Regional integration or ‘integration of spatial scales’ is considered here as the fifth dimension of integration. Regional integration aims at enhanced cooperation between regions at the landscape scale. 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 (Bull et al., 2011; Oenema 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.

5. Tools for integrated nitrogen 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, (vi) stakeholder dialogue, and (vii) Best Management Practices (BMPS). These tools are briefly discussed below.

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. 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.

A third type of tool is nitrogen balances, which quantifies the differences between nitrogen inputs and outputs of systems and of the compartments of these systems. This is an indispensable 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 (Error! Reference source not found.). The hole-in-the-pipe model also illustrates the importance of integrated N management; i.e., mitigation of an 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 (Leip et al., 2011; Oenema et al., 2003). 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 indispensable 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 Driving forces of environmental change (population growth, economic growth, etc.), to Pressures on the environment (e.g., N emissions), to State of the environment (e.g., water quality), to Impacts on population, economy and ecosystems, and finally to the Response of the society (EEA, 1995; OECD, 1991). 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, 2006). 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 (ten Brink et al., 1991). 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, manure treatment, composts production, etc.), but also for 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 indispensable 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 NH₃ control in a wider context (including dietary change). It is a good way of involving different stakeholder interests and for dealing with uncertainties.

The seventh type of tool is Best Management Practices. Best Management Practices (BMPs) are a set of activities based on the aforementioned principles, and that have been shown to yield on average the best performances. Application of BMPs depends in part on the results of the aforementioned tools of integrated N management, i.e. system analysis, N balances, integrated assessments. BMPs require farm-specific prioritization of activities and implementation of activities. There are many BMPs, because BMPs depend on (i) the objectives and their priorities, (e.g., reducing N losses, achieving high yield and NUE) and the actual/initial situation, (ii) the farm type (e.g., arable farm, vegetable farm, mixed farm, livestock farm), (iii) the socio-economic conditions (e.g., access to markets, knowledge and technology), and (iv) the environmental conditions (e.g., climate, soil, hydrology).

![Figure 3. Identification of 4 main BMP strategies, as function of the initial N input – N output situation and the tentative assumptions that (i) the nitrogen use efficiency (NUE) at farm level](image)

Figure 3. Identification of 4 main BMP strategies, as function of the initial N input – N output situation and the tentative assumptions that (i) the nitrogen use efficiency (NUE) at farm level
should range between 50 and 90% (depending on crop rotation), (ii) N output should be above 80 kg per ha per yr, and (iii) N surplus should be less than 80 kg per ha per yr (but depending on crop rotation and environmental conditions (after EU Nitrogen Expert Panel).

Four main BMP strategies can be defined for crop production systems, depending on initial situations (Figure 3). Strategy A (increasing inputs) refers to situations in Africa with decreasing yields and very high NUE due to long-term soil N mining. Strategy B (increasing yield and increasing inputs) refers to also to situations in Africa but also to various regions in Europe with low yield but acceptable NUE. Strategy C (increasing yield and decreasing inputs) refers to many situations in Europe with low yield and low NUE. Strategy D (decreasing inputs) refers to situations in intensive agricultural systems with high yield and low NUE. The latter strategy (D) does include the possibility of decreasing inputs with decreasing output; this refers to situations where the targeted output was beyond the range of the biophysical limits for acceptable NUE and N surplus.

The aforementioned four main BMP strategies for crop production systems indirectly refer to different yield response curves and to different locations on these response curves (Figure 4). Curve I refers to a low-fertility site with a ‘non-responsive crop’, i.e. N input is not limiting N output but bio-physical conditions (e.g. soil, crop variety, management) are limiting. Curve II refers to a low-fertility site with a slightly responsive crop. Curve III refers to a low-fertility site with a responsive crop, and curve IV to a low-fertility site with a highly responsive crop. Curve V refers to a high-fertility site with a responsive crop, and curve VI to a high-fertility site with a highly responsive crop, which reaches the attainable yield (N output). Highly responsive crops refer to crop varieties with a very high yield potential and optimal management (using BMPs). Responsive curves crops may refer to crop varieties with modest yield potential and optimal management (using BMPs), or to crop varieties with a high yield potential but with modest management. Non-responsive crops usually refer to either very poor soils and/or a crop with very low yield potential, and/or very poor management. In summary, response curves are the resultant of (a) Genotype (G, i.e., crop variety), (b) Environment (E, i.e., climate and soil), and (c) Management (M, inputs, allocation, methods, timing): GxE&M.

![Figure 4. Yield (N output) response curves for a low-fertility site (curves I to IV) and a high-fertility site (curves V and VI). Attainable N output is the N output achieved with BMPs for a specific combination of climate, crop type and soil type. Yield gap refers to the difference between actual and attainable N output.](image)
The four main BMP strategies will have to be combined with N loss pathway-specific measures, depending on the prevailing site specific conditions and dominant N loss pathways. Annex IX of the Gothenburg Protocol (UNECE, 1991) and the Guidance document of the UNECE Task Force on Reactive Nitrogen (Bittman et al., 2014) provide a detailed list of measures to reduce ammonia volatilization losses. The Nitrates Directive (EC, 1991) and accompanying documents provide detailed guidance for decreasing nitrate leaching losses. There are as yet no clear BMPs for decreasing N losses via nitrification-denitrification; N input control, drainage, organic matter management and soil pH management seem key measures here. Evidently, these measures (BMPs) should be elaborated further.

6. Conclusions and recommendations

Nature of the N Management Problem
- The duality of the objectives of nitrogen management in practice is both the heart of the nitrogen problem and the basis for effective N emission mitigation policy
- Understanding the natural drivers of the leaky N cycle and N transformation processes, and understanding the effects of urbanization and globalization of food systems on N cycling are prerequisites for developing more effective and efficient N policies for protecting human health, nature, biodiversity, air, and water bodies.
- The law of the optimum, the hole in the pipe model, and the interactions between nitrogen and other elements are basic ingredients for integrated N management

Key findings
- An integrated N management approach, based on a series of principles about N cycling and management, is thought to be the way forward for developing more effective and efficient N mitigation policies.
- Integrated approaches to N management make use of five possible dimensions of integration. These dimensions can be combined.
- Integrated N management makes use of a number of specific tools, including systems analysis, N balances, integrated assessment, stakeholder dialogue and communication, and best management practices.
- Best Management Practices (BMPs) are based on aforementioned principles, dimensions and tools; these measures are site specific and have been shown to yield on average the best performance.

Recommendations
- Integrated N management in EU policy should be based on the principles, dimensions and tools outlined in this chapter.
- Integrated N management measures should be introduced stepwise, starting with the integration of the measures of the Annexes II and III of the EU Nitrates Directive and of Annex IX of the Gothenburg Protocol.
- The prioritization of measures may have to be done farm specific, because farm type and environmental conditions may greatly differ between farms and hence, the effectiveness of packages of measures.
- Though farmers are considered to be the main managers, the more direct involvement of other stakeholders in the food production-consumptions chain should be considered.


