Chapter III: Principles of integrated sustainable nitrogen management

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A. Introduction and background

72. Nitrogen provides substantial benefits to society, especially by boosting crop productivity. However, nitrogen (N) losses present multifaceted problems affecting human health and the environment. These N-related problems straddle many scientific disciplines, and many domains across policy and regulation. This means that an integrated approach is required to manage N use optimally, avoiding trade-offs and allowing multiple benefits to society and the environment (Oenema and others, 2011b). As agriculture is the one sector where N is introduced intentionally to increase crop yield and quality for financial gain, it is the clearest example of why an integrated approach is required.

73. Nitrogen management in agriculture has a dual purpose: to decrease N losses to protect human health and the environment; and to optimize the beneficial effects of N related to food production. The adjectives "integrated" and "sustainable" in the title refer to the fact that N management needs to be balanced and durable – for example, environmentally sound, socially acceptable and economically profitable – for current and future generations. The negative effects of N losses on human health, ecosystem services, biodiversity, water and climate need to be addressed fully. Integrated sustainable N management contributes to achieving most of the Sustainable Development Goals. Notably, integrated sustainable N management contributes directly or indirectly to achieving Goal 1 (no poverty), Goal 2 (zero hunger), Goal 3 (good health and well-being), Goal 6 (clean water and sanitation), Goal 12 (responsible consumption and production), Goal 13 (climate action), Goal 14 (life below water) and Goal 15 (life on land). At present, the widespread evidence of adverse effects of nitrogen pollution through air, climate, land and water (Galloway and others, 2008; Fowler and others, 2013; Sutton and others, 2011, 2019; Alcamo and others, 2013) demonstrates that further action is needed to improve the effectiveness of N abatement and mitigation measures in agriculture to reduce these effects (European Environment Agency, 2015). Integrated sustainable N management provides a basis for mobilizing more sustained and coordinated action, while taking account of agroecological principles, as a basis for achieving multiple Sustainable Development Goals.

74. The purpose of this chapter is to outline the principles of integrated sustainable N management in agriculture. Section B below considers five important dimensions that any N management needs to cover to be effective. Section C describes key points of N cycling in the biosphere, to inform the reader about the nature of the N cycle in relation to agricultural practice. Section D discusses principles of nitrogen management in agriculture. Section E then presents some general tools for integrated N management. Possible measures to decrease N losses and to increase N use efficiency in agriculture are presented in subsequent chapters.

B. Dimensions of integrated sustainable nitrogen management

75. Many countries aspire to develop more integrated and effective approaches to decreasing N losses from agriculture. However, current environmental policies typically have a narrow scope as regards N management. Integration is defined here as the process of combining separate elements and aspects in an organized way, so that the constituent units are linked and function cooperatively. There are five important dimensions of integration in N management, namely:

(a) Cause and effect;
(b) Spatial and temporal integration of all N forms and sources;
(c) Multiple nutrients and pollutants;
(d) Multiple stakeholder types, involvement and integration; and
(e) Regional integration.

These dimensions build on earlier description (Oenema and others, 2011b) and are discussed further below.

1. Cause and effect

76. This dimension is a basis of all current N policies, as the human health effects and ecological impacts of the pollution caused by N emissions provide the justification for and underpin the policy measures to decrease such emissions.

77. The "cause and effect" or "source and impact" dimension is also related to the DPSIR framework (see European Environment Agency, 1995). This framework provides insights into cause-effect and economic-environmental relationships, as well as the possible responses of societies and Governments.

2. Spatial and temporal integration of all N forms and sources

78. Spatial and temporal integration in N management relates to combining all N forms, N sources and N emissions within a certain area and timescale in the management plan. Partial forms of this type of integration are contained in the Gothenburg Protocol; for example, most NO_x and NH_3 sources have been included, but NO_x emissions from agricultural soils, (semi-) natural NO_x and NH_3 sources, N_2O emissions to air and N leaching to waters are, as yet, not included when assessing compliance with emission reduction commitments. Similarly, in the European Union 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. The European Union Birds Directive[8] and Habitats Directive[9] require all N forms, N sources and N emissions to be addressed in so far as they are factors influencing the ecological requirements of protected habitats and species. The emission of gaseous N_2 through denitrification is not directly considered in any of 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 as well as a lost resource of useful nitrogen, indicating the need for N_2 emissions to also be addressed. These issues were recently raised in United Nations Environment Assembly resolution 4/14 on sustainable nitrogen management (see UNEP/EA.4/Res.14) and its follow-up in the Colombo Declaration (UNEP, 2019).

79. Conceptually, the N cascade model (Galloway and others, 2003, 2004) is a good example of spatial integration operating over different timescales, but this model has yet to be made operational for management actions. The N cascade is a conceptual model for analysing cause and effect integration, especially when cost-benefit analyses are included.

3. Multiple nutrients and pollutants

80. There are two main reasons to integrate N management with that of other specific elements (compounds) in environmental policy, namely:

(a) The other elements (compounds) may cause similar environmental effects; and

(b) Interactions between N species and these other elements and compounds may be large.

81. From a practitioner's point of view, there can be benefits when managing N and other specific elements simultaneously. This holds true, for example, for N and phosphorus (P) in agriculture and sewage waste treatment, and for NO_x and SO_2 and PM from combustion sources.

82. This type of integration is included partially in the Gothenburg Protocol and the European Union National Emission Ceiling Directive[10], which address emissions of NO_x, NH_3 and SO_2 to air, because these emissions contribute to rather similar environmental effects (air pollution, acidification, eutrophication). Similarly, emissions of N and P to surface waters both contribute to eutrophication and biodiversity loss, and thus European Union policies related to combatting eutrophication of surface waters address N and P simultaneously (for example, in the European Union Water Framework Directive[11]). Furthermore, the N and carbon (C) cycles in the biosphere are intimately linked, and perturbations of these cycles contribute to changes in the emissions of the greenhouse gases CO_2, CH_4 and N_2O, which are commonly addressed by climate change policies simultaneously. Nitrogen may also affect CO_2 and CH_4 emissions through its effect on C sequestration in the biosphere and by alteration of atmospheric chemistry (Butterbach-Bahl, Kiese and Liu, 2011a). Due to its multiple effects across all these issues, a focus on nitrogen management can serve to connect the multiple impacts and effects. Linking between the various nitrogen forms (N_2, NH_3, N_2O, NO_x, NO_3^-, etc.) serves as a manageable next step in integration. In addition, it provides a framing that demonstrates the multiple linkages between the cycles of N, C, P, sulphur (S), potassium (K), silicon (Si) and many other elements, including micronutrients.

4. Multiple stakeholder types, involvement and integration

83. Any N management policy, whether integrated or not, needs to be:

(a) Policy-relevant – for example, address the key issues;

(b) Scientifically and analytically sound;

(c) Cost effective – for example, costs have to be in proportion to the objective to be achieved; and

(d) Fair to users.

84. When one or more of these principles is not respected, the management policy will be less effective, either because of a delay in implementation or through poor implementation and performance, or a combination of those factors. Successful application of the above-mentioned principles requires communication between actors from policy, science and practice. The credibility and relevance of science-policy-practice interactions are, to a large extent, determined by "boundary" work at an early stage in the communication process between policy, science and practice (Tuinstra and others, 2006; Clark and others, 2016). Boundary work is defined here as the practice of maintaining and withdrawing boundaries between science, policy and practice, thereby shaping and reshaping the science-policy-practice interface.

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[8] Directive 2009/147/EC of the European Parliament and of the Council of 30 November 2009 on the conservation of wild birds, *Official Journal of the European Union*, L 20 (2010), pp. 7–25.

[9] Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora, *Official Journal of the European Communities*, L 206 (1992), pp. 7–50.

[10] Directive (EU) 2016/2284 of the European Parliament and of the Council of 14 December 2016 on the reduction of national emissions of certain atmospheric pollutants, amending Directive 2003/35/EC.

[11] Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy, *Official Journal of the European Communities,* L 327 (2000), pp. 1–72.

85. Communication with stakeholders (for example, fertilizer manufacturers, food producers, processing and retail, society at large) is extremely important. Such stakeholders' views must be integrated as early as possible during the design phase of N management plans and measures, notably for advisors and the practitioners who, in the end, have to implement the management measures. Integration of stakeholders' views may range from public consultation procedures and hearings to participatory approaches and learning. A good example of the latter approach is the European Union Water Framework Directive, which requires full stakeholder involvement for the establishment of river basin management plans.

86. Integration of stakeholders' views does not lead to faster decision-making; on the contrary, the decision-making process often takes more time. Public consultation procedures can be time-consuming, although techniques such as multi-criteria decision-making may support decision-making effectively. This approach aims to find a way out of conflicts and solutions in a transparent process. Integration of stakeholders' views may ultimately improve acceptance of management strategies, and thereby facilitate their implementation in practice.

Image 2: Fostering stakeholder communication is essential. Here farmers exchange views about low-protein animal feeding in dairy production (photograph: © Wageningen University & Research).

5. Regional integration

87. Regional integration or "integration of larger spatial scales" is considered here as the fifth dimension of integration. Regional integration aims at enhanced cooperation between regions and landscapes. It relates to integration of markets and harmonization of governmental policies and institutions between regions through political agreements, covenants and treaties (Bull and others, 2011). Arguments in favour of regional integration include:

(a) Enhancement of markets;

(b) Creation of a "level playing field" for policy measures;

(c) The transboundary nature of environmental pollution;

(d) Consideration of indirect pollution effects; and

(e) The increased effectiveness and efficiency of regional policies and related management measures.

88. In terms of N management, regional integration relates, for example, to the harmonization and standardization of environmental policies across the European Union and for air pollution across the UNECE region (Bull and others, 2011). The river basin or catchment management plans developed within the framework of the European Union 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 European Union Marine Strategy Framework Directive[12] also promotes integration at the regional level by ensuring consistent determinations of good environmental status and targets under its fifth qualitative descriptor (eutrophication) (see annex I to Marine Strategy Framework Directive) and coordination of programmes of measures, supported by regional sea conventions such as the Helsinki Commission for Baltic Marine Environment Protection (HELCOM) and the Convention for the Protection of the Marine Environment of the North-East Atlantic.

89. The trend towards regional integration during recent 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 true for households, farms and businesses, especially when actors can have influence on the choice of actions. In addition, motivation for contributing to the local environment and nature protection can be greater than that for contributing to the improvement of the environment in general.

C. Key points of nitrogen cycling

90. This section describes the key points of N cycling in the biosphere that underpin the N cycle in relation to agricultural practice. These key points provide the starting point from which to consider the principles of sustainable nitrogen management described further on in this document. "Principles" are understood here as "fundamental truths" and/or "well-established scientific and practical knowledge" that should be familiar to all practitioners, N managers and policymakers. The key points of nitrogen cycling also represent informing principles.

91. Ten key points related to N cycling are distinguished below. These form a "bridge" between this section and the next section, which deals with the principles of integrated N management in agriculture:

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[12] Directive 2008/56/EC of the European Parliament and of the Council of 17 June 2008 establishing a framework for community action in the field of marine environmental policy, *Official Journal of the European Union*, L 164 (2008), pp. 19–40.

Key point 1. Nitrogen is essential for life.

92. Nitrogen forms a key element of chlorophyll in plants, of haem in blood, and of amino acids (protein), nucleic acids and adenosine triphosphate in living organisms (including bacteria, plants, animals and humans). The natural nitrogen cycle is characterized by limited availability of nitrogen forms for living organisms; therefore the natural nitrogen cycle is a nearly closed system, with nitrogen being recycled and reused effectively. Due to this limited availability, nitrogen is often a limiting factor for plant growth. The competition between plant species for the limited amounts of available N (and other growth-limiting elements) is a main factor for biodiversity in natural systems.

93. In agricultural systems, significant crop-yield responses can be obtained when N is added as animal manure or fertilizer, especially when application is balanced with other key nutrients. It has been estimated that around half of the world's population is now alive because of the increased supply of fertilizer N, illustrating the massive impact that N has had in meeting human food needs, thereby allowing the world population to expand rapidly (Erisman and others, 2008; Sutton and others, 2013). Forecasts suggest that more N will be needed during the next few decades if current diets are to be matched with population increases, especially in Africa and parts of Asia (Godfray and others, 2010).

Key point 2. Excess nitrogen has a range of negative effects, especially on human health, ecosystem services, biodiversity, water and climate change.

94. The total amounts of N introduced into the global biosphere by human activities have significantly increased during the last century, more than doubling (Galloway and others, 2008), and have now exceeded critical limits for the so-called safe operating space for humanity (Steffen and others, 2015). The deleterious effects of excess N on human health and biodiversity are most apparent in regions with intensive agriculture, especially intensive animal husbandry, urban areas and in large rivers and coastal areas. Nitrogen has both warming and cooling effects on climate (Butterbach-Bahl and others, 2011b), while also contributing to stratospheric ozone depletion (Alcamo and others, 2013). The negative effects of excess N_r in the environment provide the justification for N emission-abatement policy measures.

Key point 3. Nitrogen exists in multiple forms.

95. Nitrogen is transformed from one form to another through biochemical processes, mediated by microorganisms, plants and/or animals, and through chemical processes, mediated by increased temperature and pressure, atmospheric light and possible catalysts (Smil, 2004; Hatfield and Follett, 2008; Schlesinger and Bernhardt, 2013).

96. 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 compounds (N_r) include:

(a) Inorganic reduced forms, such as ammonia (NH_3) and ammonium (NH_4^+), collectively (NH_x);

(b) Inorganic oxidized forms, for example, NO_x, nitric acid (HNO_3), nitrous acid (HONO), nitrous oxide (N_2O), nitrite (NO_2^-) and nitrate (NO_3^-);

(c) Organic reduced forms, such as urea, amines, proteins and nucleic acids.

97. Reduced forms are energy donors, proton donors and electron acceptors; energy is captured from industrial processes and biological nitrogen fixation, meaning that NH_x is an important resource. Oxidized forms are proton acceptors and electron donors. One reduced form, dinitrogen (N_2), is not reactive (it is chemically extremely stable), because a lot of energy is needed to break the bonding between the two N atoms;

98. All gaseous and liquid N_r forms are toxic to humans and animals (and plants) when exposure occurs to sufficiently high concentrations. The toxic concentration levels greatly differ between forms and among organisms. **Nitrogen is "double mobile"**, because some forms are easily transported via air and water:

(a) Nitrogen is transported in the air as gases, such as dinitrogen (N_2), nitrous oxide (N_2O), NO_x (including NO and NO_2), nitric acid (HNO_3), nitrous acid (HONO) and ammonia (NH_3), amines and other volatile organic nitrogen (VON) and as aerosols, including fine PM formed from among other things, nitrate (NO_3^-), ammonium (NH_4^+) and particulate organic nitrogen (PON);

(b) Nitrogen is transported dissolved in water as nitrate (NO_3^-), ammonium (NH_4^+), urea ($CO(NH_2)_2$), dissolved organic nitrogen (DON) and nitrous oxide (N_2O), and is transported suspended in water as particulate organic nitrogen (PON).

Key point 4. The same atom of N can cause multiple effects in the atmosphere, in terrestrial ecosystems, in freshwater and marine systems, and on human health.

99. This phenomenon is called the "nitrogen cascade", which has been defined as the sequential transfer of N_r through environmental systems and which results in environmental changes as N_r moves through or is temporarily stored within each system (Galloway and others, 2003).

Key point 5. Nitrogen moves from soil to plants and animals, to air and water bodies, and back again, and from one region to another, as a result of natural drivers and human activities, which have to be understood for effective N management.

100. The natural drivers are:

(a) Solar radiation, which drives photosynthesis, the hydrological cycle, wind and temperature differences, and mass flow in air and water;

(b) Gravitation, which drives the earth movement and erosion;

(c) Earth tectonics, which drives earthquakes and volcanisms;

(d) Lightning and biological nitrogen fixation, which form reactive N;

(e) Turbulent diffusion, molecular diffusion and Brownian motion, which drive gas and particulate dispersion.

101. The cycling rate and residence times in air, water and soil differ greatly between N forms. In the atmosphere, gases such as NH_3, NO_x, and HONO have a short residence time in air (days, weeks), while N_2O remains in the atmosphere for more than a century and N_2 even longer. Residence times are related to the reactivity of the N forms. In water systems, nitrogen residence times may range from years to many centuries depending on the nature of the aquifer and groundwater storage.

Key point 6. Human activities have greatly altered the natural N cycle and have made the N cycle more leaky.

102. Land-use change, urbanization, the creation of inorganic N fertilizer, and the globalization of food systems are among the most fundamental changes created by human activities (Vitousek and others, 1997; Fowler and others, 2013). Urbanization and the globalization of food systems have resulted in increased transport of food and feed produced in rural areas (where nitrogen depletion occurs) and to areas where food and feed are being utilized, especially in urban areas and in areas with livestock (where regional nitrogen enrichment occurs). The regional 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 (Lassaletta and others, 2014; Oita and others, 2016).

Key point 7. The nature and human alterations of the N cycle challenge the realization of both a circular economy and integrated sustainable N management; policymakers and decision makers from both areas may learn from each other.

103. Many principles of the "circular economy" and "circular systems" also apply to the principles of integrated sustainable N management, including the principles of:

(a) Reduction of losses;
(b) Reduction, reuse and recycling of wastes;
(c) Realignment and reduction of inputs;
(d) Reconsideration of protein consumption levels (for example, minimization of excess); and
(e) Changing systems to make them less leaky and more resilient.

104. The concept of the "nitrogen circular economy" (Sutton and others, 2019), and circularity more generally, originate from industrial ecology (Jurgilevich and others, 2016), which aims to reduce resource consumption and emissions to the environment by closing the loop of materials and substances, including N and other nutrients. Increasing circularity in food production requires a rethink of economic growth, human diets, agricultural policy and regulations related to fertilizers and food waste (De Boer and van Ittersum, 2018).

Key point 8. Most of the nitrogen in plants is taken from soil via roots in the form of nitrate (NO_3^-) or ammonium (NH_4^+), indicating that the NO_3^- and NH_4^+ need to be in the vicinity of plant roots and available at the right time to be effective for plant growth.

105. The N uptake depends on the N demand by the crop, the root length density and distribution and the concentrations of NO_3^- and NH_4^+ in the soil solution. The N demand by the crop depends on crop type and variety and climate. The uptake rate of N in plants commonly follows Michaelis–Menten kinetics. This implies that a maximum rate is achieved at a saturating substrate (NO_3^-, NH_4^+) concentration, so that surplus N is not used and at risk of being wasted as pollution (following the law of diminishing returns). Both the demand for N of the crop and the supply of N via the soil are influenced by soil and weather conditions and management. Dominant sources of NO_3^- and NH_4^+ in soil are (Marschner, 2012):

(a) Mineralization of organically bound nitrogen in soil;
(b) Inputs via atmospheric deposition;
(c) Inputs via animal manure, compost and wastes;
(d) Inputs via inorganic N fertilizers.

106. However, some N (for example, gaseous NH_3 and NO_2 from ambient atmospheric deposition) may be taken up directly by plant leaves (Sutton and others, 1995; Sparks, 2009). In unfertilized agroecosystems, forests and natural habitats, mycorrhizae (soil fungi living in association with plants) can play an important role in bringing nutrients to plant roots. High levels of external nitrogen input can affect the performance of such mycorrhizal symbioses.

Key point 9. Some crop types are able to convert non-reactive dinitrogen (N_2) from air into reactive N forms (amine, protein) in the plant roots through association with specialist blue green bacteria. This biological N fixation is an important source of reactive N in the biosphere, including agriculture.

107. Important crops include the legume family (Fabaceae or Leguminosae) with taxa such as (soy)beans, peas, alfalfa, clover and lupins. They contain symbiotic bacteria, especially rhizobia, within nodules in their root systems, which are able to convert N_2 into NH_3 from which amines are produced (Herridge and others, 2008). The N_2 fixation rate depends on the availability of NO_3^- and NH_4^+ in soil; the fixation rate is suppressed when the availability of NO_3^- and NH_4^+ in soil is high, and vice versa. The fixation rate also depends on the availability of substantial chemical energy (carbohydrates) and other essential nutrient elements, including phosphorus, calcium and molybdenum. Non-symbiotic N_2 fixation by free-living soil microorganisms can represent an additional input of reactive N to the ecosystems (Ladha and others, 2016).

Key point 10. Humans and animals require protein-N and amino acids for growth, development and functioning, but only a minor fraction of the N is retained in the growing body weight and/or milk and egg.

108. The remainder is excreted, mainly via urine and faeces, and this N can be recycled and reused. The protein N need (or amino acid requirements) of animals mainly depends on animal category, body weight, growth rate, milk and egg production, activity (labour, grazing) and reproduction (McDonald and others, 2010; Suttle, 2010). The N retention in animal production is strongly dependent on animal breed,

feed quality, age and herd management, and commonly ranges from 5 to 15 per cent in beef production, 15 to 30 per cent in dairy production, 25 to 40 per cent in pork production and 40 to 50 per cent in poultry production (Gerber and others, 2014). The remainder is excreted as urea in urine (uric acid in poultry) and in animal manure. Typically, half of N excretion is in the form of urea (and ammonium (NH_4^+)) and half in organically bound form, depending on the protein content of the feed. Animal manure and urine provide a valuable source of nutrient elements and organic C in natural and agricultural systems. However, animal manures and urine are also main sources of ammonia (NH_3) and nitrous oxide (N_2O) emissions to air, and of N leaching to groundwater and surface waters, depending on management and environmental conditions.

D. Principles of integrated sustainable nitrogen management in agriculture

109. Twenty-four principles of integrated sustainable nitrogen management are identified:

Principle 1: The purpose of integrated sustainable nitrogen management in agriculture is to decrease nitrogen losses to the environment to protect human health, climate and ecosystems, while ensuring sufficient food production and nitrogen use efficiency, including through appropriately balanced nitrogen inputs.

110. As the key input, along with water, the importance of N for food security cannot be overstated. The effectiveness of integrated sustainable N management in agriculture can be assessed through applying consistent metrics (see box III.1).

Principle 2: There are various actors in agriculture and the food chain, and all have a role and responsibility in N management.

111. These actors include:

(a) Suppliers of fertilizers, feed, germplasm, seed, machinery and loans;

(b) Advisors, extension services, accountancy specialists and financial organizations;

(c) Farmers;

(d) Product handling and processing industries (crop products, dairy, meat, manure);

(e) Retail organizations;

(f) Consumers;

(g) Governments and NGOs, including food testing; and

(h) Scientists.

112. Evidently, farmers have a direct role to play in N management, in enhancing N use efficiency and in minimizing N losses to the environment. Therefore, farmers reap the economic benefits and bear the burdens of the measures needed to decrease N losses. Incorporation of certain N measures offers net economic benefits that can contribute to farm business planning and circular economy development. For other measures, the costs of implementation exceed the agricultural benefits arising from the greater retention of N in the agricultural system, and may only be justifiable from an environment, health and climate perspective. The net costs are as yet difficult to transfer to (spread over) other actors in the food production – consumption chain, because farmers have little or no "market power" in a globalized food system. Farmers may be reluctant to implement costly measures to reduce N losses because they want to maximize income and fear losing competitiveness relative to farmers who do not implement measures. Providing access to funding/financing via appropriate instruments may therefore need to be considered as part of the policy to support the transition to more integrated sustainable nitrogen management. **There is thus a joint responsibility for all actors in the food chain, including for policymakers at several levels, to support a decrease of N losses and to share the cost and benefits of N abatement/mitigation measures. This should be done in concert with other critical policies, including mitigating climate change.**

Principle 3: Specific measures are required to decrease pathway-specific N losses.

113. The dominant N loss pathways in agriculture are:

(a) NH_3 volatilization;

(b) Downward leaching of (mainly) nitrate to groundwater and then to surface waters;

(c) Overland flow and erosion of basically all N forms to surface waters; and

(d) Nitrification-denitrification processes combined with the gaseous emissions of NO_x, N_2O and N_2.

114. These pathways are influenced by a complex of controlling factors, including the availability and form of N sources, climate, soil and geomorphological/hydrological conditions and management. **Pathway-specific measures have to consider pathway-specific controlling factors** (Hatfield and Follett, 2008; Bittman and others, 2014; UNECE, 2013).

Principle 4: Possible trade-offs in the effects of N loss abatement measures may require priorities to be set, for example, which adverse effects should be addressed first.

115. In practice, the outcome will depend on a quantification – a small negative effect of one kind may be tolerated when there is a huge improvement elsewhere – and on policy guidance on how to compare the importance of issues (for example, N eutrophication versus greenhouse gas emissions through N_2O emissions versus human health effects through NH_3 emissions and associated formation of small particles $PM_{2.5}$ (Sutton and others, 2011)). There may also be non-N agricultural trade-offs, and even non-agricultural trade-offs. Policy guidance is necessary to inform such priorities and properly weigh the options according to local to global context and impacts.

Principle 5: Nitrogen input control measures influence all N loss pathways.

116. These are attractive measures to decrease N losses in an integrated manner, because reductions in nitrogen input (for example, by avoidance of excess fertilizer, of excess

Box III.1: Metrics for assessing the effectiveness of integrated sustainable nitrogen management.

One of the core purposes of integrated sustainable nitrogen management in agriculture is to decrease N losses to the environment to protect human health, ecosystems, climate and other aspects of economy and sustainability, while ensuring adequate crop and animal production (principle 1).

Indicators to reflect this principle have been proposed by the European Union Nitrogen Expert Panel (Oenema and others, 2015), with a focus on Nitrogen Use Efficiency (NUE):

NUE = Sum of N outputs / Sum of N inputs ......(percentage, per cent)
N surplus = Sum of N inputs – Sum of N outputs ......(kg N /ha /yr)
N in harvested or other utilized outputs ......(kg N /ha /yr)

Evidently, a high NUE indicates that N input is being used efficiently. A low N surplus indicates that the potential for N loss and impacts on the environment is low, with a large part of the N input recovered in N in harvested products. The approach is relevant from multiple perspectives, for crops, livestock, agrifood system and across the economy (Bleeker and others, 2013; Sutton and others, 2013; Westhoek and others, 2015; Erisman and others, 2018).

The effects of measures aimed at the abatement of specific nitrogen loss pathways are commonly expressed in terms of abatement efficiency (AE), reduction in N loss and overall change in NUE:

AE = (Unabated N loss – Abated N loss) / Unabated N loss ......(percentage, per cent)
Total reduction in N loss ......(kg N /ha /yr)
Change NUE = (NUE revised – NUE reference) / NUE reference ......(percentage, per cent)

Another approach focused on reducing overall environmental impact considers global and national reduction in total "nitrogen waste", this being the sum of all nitrogen losses to the environment (including N_2 and all N_r forms). This approach is reflected in the ambition of the Colombo Declaration (UNEP, 2019; Sutton and others, 2019) to "halve nitrogen waste" from all sources, as a contribution to achieving the United Nations Sustainable Development Goals:

$$\text{Reduction in total N waste} = \frac{\text{(Reference N waste-Revised N waste)}}{\text{(Reference N waste)}} \quad \text{......(percentage, per cent)}$$

Whereas AE focuses on the performance of specific measures on each form of N loss, the reduction in total N waste emphasizes the benefit of all reductions in N losses, by all approaches at national, regional and global scales. Further work is needed to agree international protocols for each of these indicators to assist countries in preparing data sets and to enable informed comparison of different indicator values and target values.

protein in animal diets, and of any human foods with high nitrogen footprint) lead to less nitrogen flow throughout the soil-feed-food system, reducing losses of all forms of nitrogen pollution. For example, Westhoek and others (2015) showed that halving meat and dairy intake by European citizens (which is currently in excess of health needs) would reduce nitrogen pollution by 40 per cent (for NH_3) and by 25–40 per cent (for N_2O and NO_3^- leaching) in the absence of any technical measures. The reason for the range for N_2O and NO_3^- is that substantial agricultural land would also be liberated for other purposes, allowing alternatives such as increased crop production for export (net 25 per cent abatement) or "greening measures", which deliver the maximum reduction in nitrogen pollution (net 40 per cent abatement). Further assessments are needed to consider the impact of consuming unessential, non-livestock-based foods and beverages.

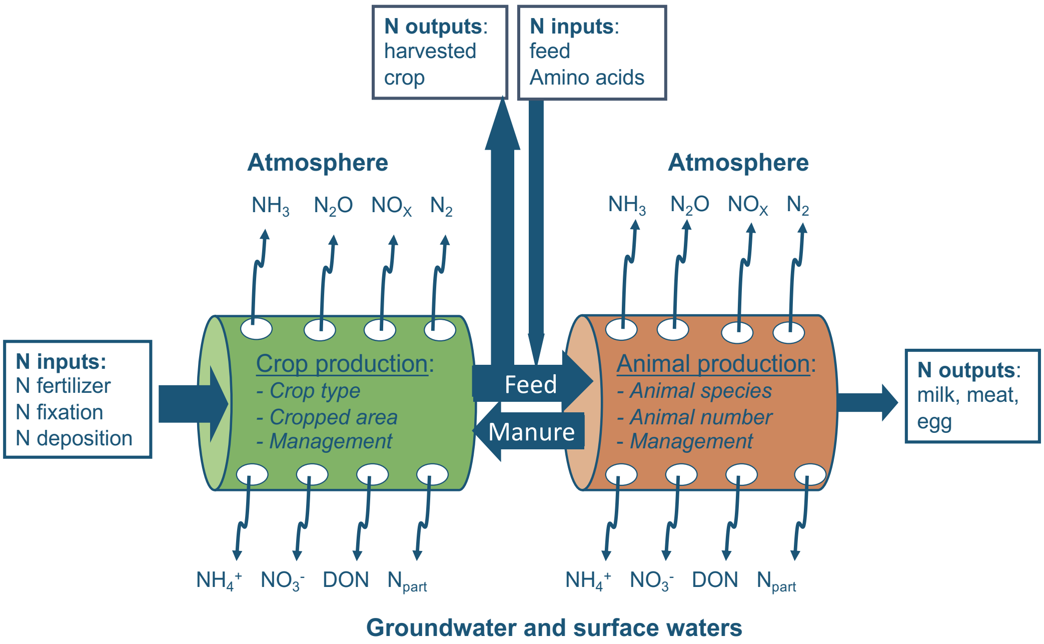
Principle 6: A measure to reduce one form of pollution leaves more N available in the farming system, so that more is available to meet crop and animal needs.

117. This means that reducing one form of N loss involves the risk of increasing other forms of N losses, sometimes termed "pollution swapping", unless inputs and outputs (including N storage in soils) are changed. In order to realize the benefit of a measure to reduce N losses (and to avoid pollution swapping), the nitrogen saved by the measure needs to be matched by either reduced N inputs or increased N in harvested outputs (including N storage in soil). Reduced N inputs or increased harvested outputs are thus an essential part of integrated nitrogen management, while providing opportunity for increased economic performance (Oenema and others, 2009; Quemada and others, 2020).

Principle 7: The N input-output balance encapsulates the principle that "what goes in must come out", making it a key indicator of N management.

118. Based on the law of mass conservation, inputs must match outputs or be temporarily stored within the farm

Figure III.1: Concept of the nitrogen input – output mass balance of mixed crop – livestock production systems



Source: Modified from Oenema and others (2009).

Note: The "hole-in-the-pipe" model (after Firestone and Davidson, 1989) illustrates the "leaky N cycle" of crop and animal production; it shows the fate of N inputs in agriculture. Inputs and 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. The concept is applicable at field, farm, regional and global scales for all types of farms (Oenema and others, 2009

system. Hence, N input = N output in harvested products (+ temporal N storage) – N losses (see figure III.1). It illustrates also that N input control is a main mechanism to reduce N losses. It also allows for strategies based on maximization of N in storage pools, including in manure, soil and plants (for example, by promoting plant uptake of N). Internationally agreed protocols are needed for making these N input-output balances; N inputs and N outputs must be recorded in a uniform manner to allow fair comparisons between farms and regions, and to circumvent bias.

Principle 8: Matching nitrogen inputs to crop-needs (also termed "balanced fertilization") and matching protein N inputs to livestock needs offers opportunities to reduce all forms of nitrogen losses simultaneously that can help to improve economic performance at the same time.

119. Hence, increasing "partial factor productivity" (defined as harvest output per unit of N input) increases N use efficiency and reduces all forms of N losses. This follows directly from the above-mentioned law of mass conservation. Furthermore, the law of diminishing returns must be considered when matching N inputs to crop needs; with increasing N input, crop yield and N uptake increase only marginally, while N losses tend to increase progressively. These basic principles equally hold true for crop and animal production and overall food production.

Principle 9: Spatial variations in the vulnerability of agricultural land to N losses require spatially explicit N management measures in a field and/or landscape (including with the aid of precision farming techniques and tools).

120. The surface of land is often sloping and soils are often heterogeneous in nature, while the weather is variable and uncertain, which indicates that crop growth conditions, soil N delivery and N loss pathways are variable in space and time. Such spatially diverse conditions can only be addressed by locally fine tuning agricultural management techniques (such as "precision farming" techniques, where management actions are adjusted for each field location) and use of site-specific emission-abatement measures. This principle is applicable to field application of both organic and inorganic fertilizer resources (see chapter V).

Principle 10: Spatial variations in the sensitivity of natural habitats to N loadings originating from agriculture highlight the need for site- and region-specific N management measures.

121. A source-pathway-receptor approach may help to target specific hot spots, specific N loss pathways and specific sensitive areas. This holds true especially for natural habitats that are sensitive to N loading in an agricultural landscape with intensive livestock farms; the latter are likely hot spots for NH_3 emissions, while the natural habitats are likely highly sensitive to N inputs via atmospheric deposition. The same principle applies to drinking water reservoirs, pristine lakes, streams and coastal waters; these need special protection to prevent pollution. This principle underlies added benefits from landscape-level N management (see chapter VI).

Principle 11: The structure of landscape elements affects the capacity to store and buffer nitrogen flows. This means that ecosystems with high N storage capacity (for example, woodlands and unfertilized agricultural land) tend to buffer the effects of N compounds emitted to the atmosphere, so that less N is transferred to other locations.

122. This principle equally applies to unfertilized buffer strips and riparian zones along N sensitive watercourses. Woodlands and unfertilized agricultural land are land-uses with capacity to absorb and recycle (utilize) N inputs from atmospheric N deposition (for example, Dragosits and others, 2006; cf. chapter VI). Border areas and transition zones also offer habitat for biodiversity in an agricultural landscape for vulnerable organisms such as pollinators. In this way, woodlands, extensive agricultural land and other landscape features help absorb and utilize N inputs from atmospheric N deposition or N that would otherwise be lost through lateral water flow. This principle is the basis of planning to increase overall landscape resilience, where, for example, planting of new woodland (with the designated function of capturing N) can be used as part of a package of measures to help protect other habitats (including other woodland and ecosystems where nature conservation objectives are an agreed priority). However, woodland soils receiving high N deposition over the long-term may transform from a sink to a source of N_r pollution; for example, emitting NO_x (Luo and others, 2012; Medinets and others, 2019). This also holds true for buffer strips and riparian zones along water courses; the capacity to utilize or store reactive N and/or to transform reactive N into N_2 may change over time (chapter VI).

Principle 12: In order to minimize pollution associated with N losses, all factors that define, limit and reduce crop growth need to be addressed simultaneously, and in balance, to optimize crop yield and N use efficiency.

123. Crop yield, N uptake and N use efficiency depend on:

(a) Yield-defining factors (crop type and variety, climate);

(b) Yield- limiting factors (availability of all 14 essential nutrient elements and water, and soil quality); and

(c) Yield-reducing factors (competition by weeds, incidence of pest and diseases, occurrence of highly soluble salt and/or toxic compounds in soil, and air pollution (for example, ozone) (van Ittersum and Rabbinge, 1997).

124. 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 (De Wit, 1992). This will thus have an impact on N losses to the environment. Hence, optimizing yield and N use efficiency and reducing N losses in crop production requires an integrated approach:

(a) Selecting high-yielding crop varieties, adapted to the local climatic and environmental conditions;

(b) Preparing seedbeds according to crop seed type prior to seeding/planting and providing adequate levels of all essential nutrient elements and water; and

(c) Ensuring proper weed control, pest and disease management and pollution control.

125. As a result of the complex factors involved, yield optimization remains challenging. For example, the important beneficial and negative effects of crop sequences are not fully understood. There are emerging issues of pesticide resistance, invasive species, climate change, etc.

Principle 13: In order to minimize pollution associated with N losses, all factors that define, limit or reduce animal growth have to be addressed simultaneously and in balance to optimize animal production and N use efficiency, which can also decrease N excretion per unit of animal produce.

126. Animal production and N retention in animal products also depend on:

(a) Yield-defining factors (animal species and breed, climate);

(b) Production-limiting factors (feed quality, availability of all 22 essential nutrient elements and water); and

(c) Production-reducing factors (diseases, fertility, toxicity, air pollution, for example, ammonia, H_2S, ozone).

127. According to the Law of the Optimum, optimizing animal production and N use efficiency in animal production and decreasing N losses requires an integrated approach:

(a) Selecting animal species and breeds adapted to the local climatic and environmental conditions;

(b) Ensuring availability of high-quality feed and water, good feeding management and herd management; and

(c) Ensuring proper disease, health, fertility and pollution control, including animal welfare aspects (McDonald and others, 2010; Suttle, 2010).

128. Optimization must take into account the reproductive phase, including the number of lactations, conception rates, birth weight, etc. This principle and the previous one hold true equally well for mixed crop and animal production systems.

Principle 14: Slowing down hydrolysis of urea and uric acid containing resources helps to reduce NH_3 emissions.

129. Hydrolysis of these resources produces NH_3 in solution and increases pH, so slowing hydrolysis helps avoid the highest ammonium concentrations and pH, which can also reduce other N losses by avoiding short-term N surplus. This principle underlies several measures in manure and fertilizer management. For example, immediate separation of urine from faeces can reduce NH_3 emissions because urine contains most urea, while faeces are rich in the enzyme urease that breaks down urea to release CO_2 and NH_3. The same principle underlies the benefit of keeping poultry litter dry to avoid breakdown of uric acid, which similarly releases NH_3. "Urease inhibitors" are substances added to urea fertilizer to reduce NH_3 and other N losses. By reducing the effectiveness of the urease enzyme, these products slow down urea hydrolysis (Bitmann and others, 2014).

Principle 15: Reducing the exposure of ammonium-rich resources to the air is fundamental to reducing NH_3 emissions.

130. Hence, reducing the surface area and covering ammonium-rich resources reduces NH_3 emissions. Lowering the pH (to ≤6.5) of ammonium-rich resources also lowers

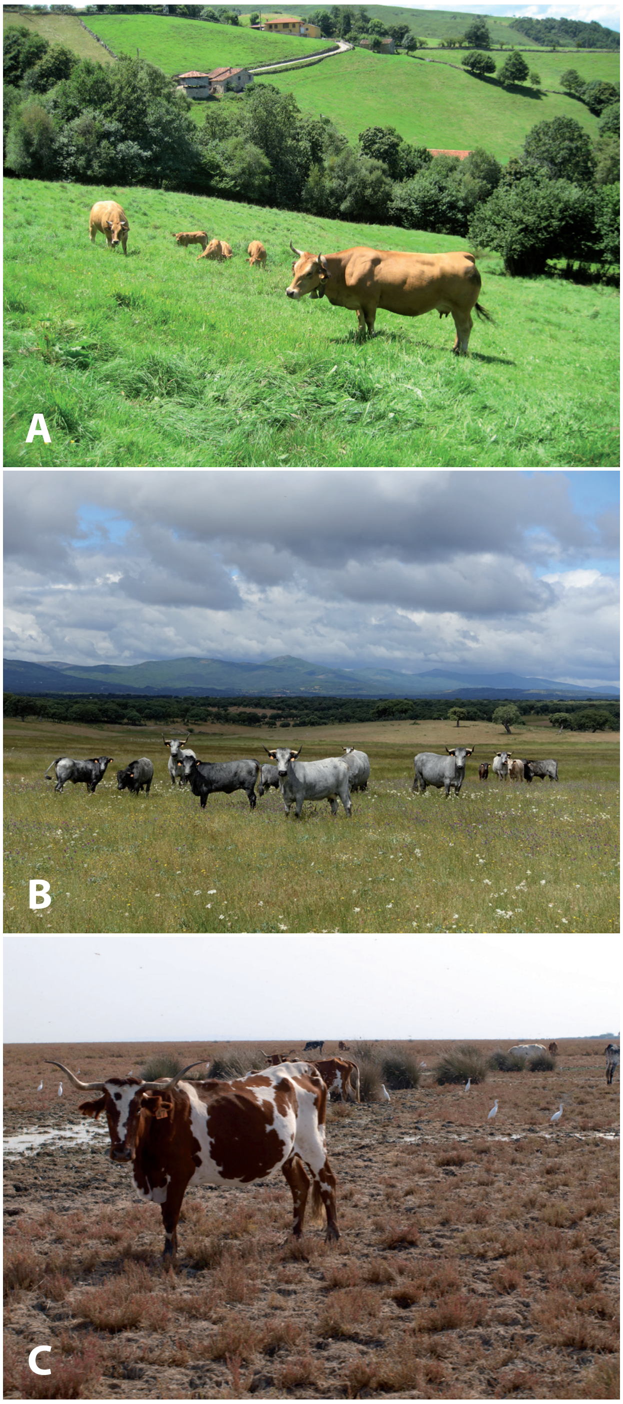


Image 3: Allowing animals to graze substantially reduces ammonia emissions due to rapid infiltration of urine and plant uptake (**A**, **B**, relevant for principle 15). However, poor grazing conditions can increase other nitrogen losses (e.g., standing water, lack of vegetation; **C**, relevant for principle 4) (photograph © Ministerio Agricultura, Pesca y Alimentación, Spain, 2021).

NH_3 emissions. Lowering the temperature of ammonium-rich resources and the wind speed above the surface also reduces NH_3 emissions. All these emission-abatement techniques must be applied with consideration to a whole manure management chain approach, to minimize the loss at later stages of any N retained during the first part of the management chain (Bittman and others, 2014).

Principle 16: Slowing down nitrification (the biological oxidation of NH_4^+ to NO_3^-) may contribute to decreasing N losses and to increasing N use efficiency.

131. Because of its positive charge, NH_4^+ can be held in soil (depending on the cation exchange capacity of the soil). This means that NH_4^+ is less mobile and less vulnerable to losses via leaching and nitrification-denitrification processes than NO_3^-, the other dominant N form in soil utilized by crops. Therefore, promoting conditions that slow down the biological oxidation of NH_4^+ to NO_3^- may contribute to a reduction of N losses and to increasing N use efficiency. Synthetic nitrification inhibitors and biological nitrification inhibitors exuded by plant roots and leaves slow down nitrification and help conserve N in the system and thereby may increase N use efficiency. However, the possible (long-term) side effects on soil health (including the soil microbial community) of such strategies have to be considered (Medinets, and others, 2015; Lam and others, 2017; Coskun and others, 2017; Norton and Ouyang, 2019).

Principle 17: Some measures aimed at reducing N_2O emissions may also reduce losses of N_2, since both are related to denitrification processes.

132. Conversely, measures aimed at minimizing denitrification to N_2 may also reduce N_2O emissions. Nitrogen losses from agriculture via the greenhouse gas N_2O represent a relatively small loss, but N_2O is a potent greenhouse gas and contributes to the depletion of stratospheric ozone (UNEP, 2013). The associated N_2 loss via nitrification-denitrification represents a much larger loss of N resources, although N_2 losses do not have a direct negative effect on the environment. Hence, measures aimed at jointly reducing N_2O and N_2 losses from nitrification-denitrification processes may contribute to saving N resources within the system at the same time.

Principle 18: Achieving major N_2O reductions from agriculture necessitates a focus on improving N use efficiency across the entire agrifood system using all available measures.

133. This requires consideration of system-wide changes in human diets, livestock diets, management of fertilizer and biological and recycled nitrogen resources. The requirement for wider system change is because of the modest potential of specific technical measures to reduce N_2O emissions from agricultural sources compared with ambitious reduction targets for climate and stratospheric ozone (Oenema and others, 2013; UNEP, 2013; Cayuela and others, 2017; Thompson and others, 2019). At the same time, a focus on improving full system efficiency provides a positive approach that highlights the economic, environment and health co-benefits.

Principle 19: Strategies aimed at jointly decreasing N, P and other nutrient losses from agriculture are expected to offer added abatement/mitigation benefits compared with single nutrient emission-abatement strategies, because of the coupling between nutrient cycles.

134. For example, interactions between N and P affect the efficiencies of N and P use in crop and animal production, as well as their impacts on the eutrophication of surface waters. A suboptimal availability of P limits the uptake and

utilization of N and P in crop and animal production and may limit eutrophication effects of N in surface waters. Conversely, a suboptimal availability of N limits the uptake and utilization of P in crop and animal production and may limit the eutrophication effects of P in surface waters (Conley and others, 2009). However, overoptimal availability of N and P decreases both N and P use efficiencies, greatly increases the risk of both N and P losses, and exaggerates their eutrophication effects in surface waters. Furthermore, total losses of both N and P have already been estimated to exceed "planetary boundaries", which indicates that both N and P losses have to decrease greatly (Steffen and others, 2015; Springmann and others, 2018). While these points illustrate scientific reasons for linked management of nutrient cycles (Sutton and others, 2013), there are also social and political barriers that must be addressed, related to the development of multisector narratives (air, water, climate, etc.) and sector sensitivities concerning mobilization of change. In this way, a nitrogen focus provides a pragmatic approach that encourages links between multiple threats and element cycles, thereby accelerating progress.

Principle 20: Strategies aimed at optimizing N and water use jointly are more effective than single N fertilization and irrigation strategies in semi-arid and arid conditions.

135. Interactions between N and water affect the N and water use efficiencies in crop production, as well as affecting all N loss pathways (Quemada and Gabriel, 2016). A suboptimal availability of water limits the uptake and utilization of N in crop production, and can reduce N leaching and denitrification losses, according to soil characteristics; it may lead to accumulation of nitrate-N in soil. In addition, rainfall and sprinkler irrigation may reduce N losses via NH_3 volatilization from urea fertilizers and animal manures applied to land (Sanz-Cobena and others, 2011). Conversely, a suboptimal availability of N limits water use efficiency in crop production. The joint coupling of N and water management also underlies the safe storage of solid manures to avoid run-off and leaching. However, an overoptimal availability of N and water decreases both N and water use efficiencies, and greatly increases the risk of N losses via leaching, erosion and denitrification. Application of targeted amounts of water and N through drip irrigation (fertigation) in semi-arid regions has the potential to greatly increase N and water use efficiencies simultaneously, and to minimize N losses. Furthermore, crop yields at the global scale are mostly limited by the availability of both water and N (Mueller and others, 2012). This underlines the need for an integrated approach in which the availability of both N and water are considered jointly, especially in those regions of the world where food production is limited by the availability of both water and N, and where food production has to increase to meet the demands of the growing human population (Godfray and others, 2010). Irrigation must be used judiciously to conserve water and to avoid soil salinization, especially on fine textured soils.

Principle 21: Strategies aimed at enhancing N use efficiency in crop production and at decreasing N losses from agricultural land have to consider possible changes in soil organic C and soil quality over time and the impacts of soil C sequestration strategies.

136. The carbon-to-nitrogen ratio in organic matter in soil ranges roughly from 10 to 15 (exceeding 30 in organic soils). This rather narrow range has a number of implications. First, C sequestration in soil aimed at reducing carbon dioxide (CO_2) emissions to the atmosphere and improving soil quality is associated with N sequestration in soil. If this results in a lower C:N ratio and hence a higher turnover of N in the soil, there is a risk that this could increase losses of N (including direct and indirect N_2O emissions), especially when there is little crop uptake. Second, storing organic C in soil means that the organic C first has to be produced. While this might be achieved by increasing crop production, there is a risk that the management required to increase the input of C to the soil (i.e. crop residues) might result in a reduction in N use efficiency. For example, achieving the objectives of the "4 per 1,000" initiative[13] may lead to a storage of N in soil nearly equivalent to the current annual global N fertilizer use (Van Groenigen and others, 2017). The possible interactions between C and N in soil and the effects of soil quality and N use efficiency must therefore be taken into account in integrated N management strategies (Cassman, 1999). In addition, protection of soil organic matter against degradation by, for example, excessive tillage (N mining) and erosion must have high priority to be able to sustain agricultural productivity, especially in regions with low N input; for example, Africa and Eastern Europe (Boincean and Dent, 2019).

Principle 22: Strategies aimed at reducing NH_3 emissions from animal manures through low-protein animal feeding need to consider the possible impacts of diet manipulations on enteric methane (CH_4) emissions from ruminants.

137. Protein-rich diets are conducive to a relatively high N excretion, and the resulting manures have a high potential for NH_3 volatilization losses. Conversely, low-protein diets are conducive to a relatively low N excretion, and the resulting manures have a low potential for NH_3 volatilization losses. However, some low-protein diets may have relatively high-fibre content, which is conducive to enteric CH_4 production in ruminants (Dalgaard and others, 2015). Methane is a potent greenhouse gas and ruminants are one of the main sources of CH_4 emissions to the atmosphere in the world. Evidently, the aim is to find the optimal protein and fibre levels in the diet of ruminants, to minimize both NH_3 and CH_4 emissions (Bittman and others, 2014; Hristov and others, 2019; Van Gastelen and others, 2019). For ruminants especially, it is important to balance protein degradability (and possibly tannins) with energy level and availability such as high sugar concentrations, which may also improve palatability and intake. High sugar content may improve the ensiling process thus reducing losses by spoilage.

Principle 23: The cost and effectiveness of measures to reduce losses of N need to take account of the practical constraints and opportunities available to farmers in the region where implementation is intended.

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[13] See www.4p1000.org.

Image 4: Education about nitrogen practices is needed to widen awareness (photograph: © Shabtai Bittman).

138. The effectiveness and costs must be examined as much as possible under practical farm conditions, while taking particular account of farm size and basic environmental limitations. Management practices need to be tested on-farm and good practices need to be shared among the farming community. Socioeconomic factors, such as the educational and age structure of the farming population, availability of skilled labour and good advice and access to finance, are important. Cost-effectiveness analysis should take into consideration the implementation barriers as well as the side effects of practices on other forms of N and greenhouse gases, in order to promote co-benefits.

Principle 24: The whole-farm level is often a main integration level for emission-abatement/mitigation decisions, and the overall effectiveness of emission-abatement/mitigation measures will have to be assessed at this level.

139. Interactions between different measures and interactions between N losses and greenhouse gas (GHG) emissions can be assessed well at the whole-farming system level, including consideration of the wider landscape, regional and transboundary interactions.

E. Tools to support integrated nitrogen management

140. The toolbox for developing integrated approaches to N management contains tools that are uniformly applicable, as well as more specific tools suitable for just one dimension of integration. Important common tools are:

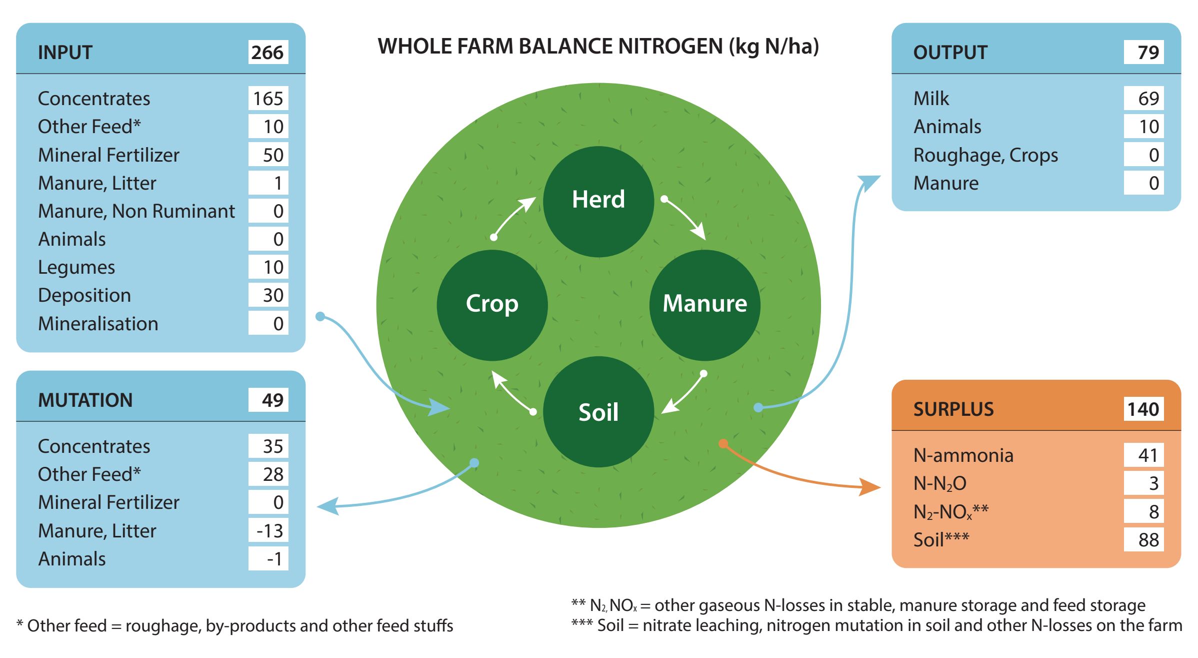
(a) Systems analysis;
(b) N input-output budgeting;
(c) Integrated assessment modelling and cost-benefit analyses;
(d) Food-chain management;
(e) Stakeholder dialogue and communication; and
(f) So called Best Management Practices (BMPs).

141. These tools for integrated nitrogen management approaches in general are briefly discussed below. Specific measures are discussed in chapters IV–VI:

(a) **Systems analysis** represents the starting point for developing integrated approaches, as it provides information that is needed for all dimensions of integration. Systems analysis allows for the identification and quantification of components, processes, flows, actors, interactions and interlinkages within and between systems. It provides a practical tool for discussing integrated approaches to N management. In essence, system analysis encompasses the view that changes in one component will promote changes in all the components of the systems. These types of tools are especially useful at the science-policy-practice interface.

(b) **Nitrogen budgets** allow the comparison of nitrogen inputs and outputs of systems (for example, a farm, a catchment, a country) and of the compartments of these systems. Nitrogen budgets are an indispensable tool as they integrate over N sources and N species for well-defined areas and/or components (Zhang and others, 2020). They allow calculation of the "nitrogen balance", which is the difference between total inputs and total outputs. The nitrogen balance reflects the amount of N stored or removed from the system plus the N losses from the system to the wider environment. Input-output balances are robust and easy-to-understand management tools for farmers (Jarvis and others, 2011) and policymakers. They are useful in that they help set priorities in optimizing inputs and in reducing unintended losses, also providing the basis for monitoring system efficiency or surpluses likely to be wasted. Nitrogen budgets are flexible tools, but require protocols (such as appropriate default values for N concentrations for various materials) for recording N inputs and N outputs in a uniform manner, so as to allow fair comparisons between farms and across sectors, and to avoid bias (Leip and others, 2011; UNECE, 2013).

(c) **Integrated assessment modelling** allows relationships between emissions, emissions-abatement, environmental impacts and benefits of effects mitigation to be simulated, including consideration of cost-benefit relationships and target setting. Integrated assessment modelling may also analyse the possible effects of responses by society (actors) through scenario analysis. The DPSIR framework can be used as a starting point for conceptually analysing cause-effect relationships; it relates Driving forces of environmental change (for example, population growth, economic growth, technology development), to Pressures on the environment (for example, N_r emissions), to State of the environment (for example, N concentrations in air and waters, and N deposition on natural habitats), to Impacts (for example, human health, biodiversity, economic growth, eutrophication, ecosystems services) to the Responses of society (for example, policy measures, changes in behaviour; EEA, 1995). Examples of integrated assessments include reviews of the Gothenburg Protocol by the Task Force on Integrated Assessment Modelling (TFIAM/CIAM, 2007). Cost benefit analysis (CBA) goes a step further by expressing costs and benefits of policy measures in monetary terms (Hanley and Barbier 2009; OECD, 2018). Strategic environmental assessment



INPUT	266
Concentrates	165
Other Feed*	10
Mineral Fertilizer	50
Manure, Litter	1
Manure, Non Ruminant	0
Animals	0
Legumes	10
Deposition	30
Mineralisation	0

MUTATION	49
Concentrates	35
Other Feed*	28
Mineral Fertilizer	0
Manure, Litter	-13
Animals	-1

OUTPUT	79
Milk	69
Animals	10
Roughage, Crops	0
Manure	0

SURPLUS	140
N-ammonia	41
N-N_2O	3
N_2-NO_x**	8
Soil***	88

* Other feed = roughage, by-products and other feed stuffs

** N_2,NO_x = other gaseous N-losses in stable, manure storage and feed storage
*** Soil = nitrate leaching, nitrogen mutation in soil and other N-losses on the farm

Image 5: Illustration of a whole farm nitrogen balance for a dairy farm. Such approaches can help set priorities for reducing nitrogen pollution and wasted nitrogen resources (image redrawn from image © Wageningen University & Research).

(SEA) has also been suggested as a useful tool. SEA is a systematic decision-support process, aiming to ensure that environmental aspects are considered effectively in policy planning and programme making (Fischer, 2007; Ahmed and Sánchez-Triana, 2008). The UNECE Protocol on Strategic Environmental Assessment to the Convention on Environmental Impact Assessment in a Transboundary Context sets legally binding requirements.

(d) **Food-chain assessment and management** relates to the planning and management of activities and information between actors in the whole food production – consumption chain, including suppliers, processing industries, retail, waste-recycling companies and citizens. In essence, food-chain management integrates the supply and demand of information and activities within and across all actors in the whole chain (Erisman and others, 2018). Specific issues relate to:

(i) How to ensure that consumers have access to and are aware of nutritious food, and have information about sustainable food choices;

(ii) How consumers' demands can be met by the producers, in terms of, for example, quality, production methods and N footprint;

(iii) How the costs of emission-abatement measures implemented by producers are remunerated across the actors of the food chain; and

(iv) How food waste and losses can be minimized and how all wastes in the food chain can be recycled back to crop land. This type of chain management is still poorly developed, apart from in specific sectors and food-processing chains.

(e) **Stakeholder dialogue and communication** are indispensable for exchanging actors' views on N management issues. Stakeholder dialogue is the 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. Communication is both the transferral of information and the means of raising awareness among and explaining the meaning, purpose, targets and actions of integrated approaches to N management to all the actors concerned. 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 (and training) can help make the key concepts transparent and thereby facilitate adoption of targets and implementation of agreed measures in practice.

(f) **Best management practices and abatement/mitigation measures**. The concept of best management practices (BMPs) includes best available techniques (BATs) and best system practices (BSPs). In the case of nitrogen, they encompass a set of activities and techniques based on the above-mentioned principles for integrated sustainable nitrogen management. A possible definition of BMPs could be management practices that have been shown to yield on average the best performances in practice. This means that, when agreeing on and assigning BMPs, those involved must first agree on the relevant performance criteria and their weighting. As a consequence, there are many views of BMPs, as they depend on:

(i) The objectives (for example, reducing N losses, achieving high yield and making sure that the most appropriate N use efficiency and/or water use efficiency values are applied, farm-scale cost-benefit, societal cost-benefit);

(ii) The farm type (for example, arable farm, vegetable farm, mixed farm, livestock farm);

(iii) The socioeconomic conditions (for example, access to markets, knowledge and technology); and

(iv) The environmental conditions (for example, climate, soil, hydrology).

142. Given this complexity and recognizing differences of opinion as to what approach or level-of-ambition constitutes "best", options in chapters IV–VI are simply referred to as "measures". The measures are actions focused on abatement of emissions or mitigation of adverse effects, or both.

F. Conclusions and recommendations

143. The following conclusions can be drawn regarding the principles of integrated sustainable nitrogen management:

(a) The purpose of integrated sustainable nitrogen management in agriculture is to minimize nitrogen losses to the environment and to protect human health, ecosystems and climate, while ensuring adequate levels of crop and animal production and N use efficiency through balanced fertilization and circular economy principles. The negative effects of N losses on human health, ecosystem services, biodiversity, water and climate need to be fully addressed;

(b) It is important to have an understanding of the drivers of the leaky N cycle and N transformation processes. This underpins understanding of how intensification and regional specialization of agriculture systems affect N cycling. Such understanding is a prerequisite for developing effective N policies for protecting air, soil and water in order to preserve human health, climate and biodiversity;

(c) The Law of the Optimum, the "hole-in-the-pipe" model (see figure III.1) and appreciation of the interactions between nitrogen and other elements are key reasons for focusing on integrated N management;

(d) An integrated and sustainable N management approach, based on a series of key points regarding N cycling and management, is the foundation for efficient N abatement/mitigation policies and sustainable agricultural practices that help stimulate an emerging nitrogen circular economy;

(e) Integrated approaches to sustainable nitrogen management make use of five possible dimensions of integration (chapter III, section B) These dimensions can be combined;

(f) Integrated and sustainable N management makes use of the five following tools, which can be combined: systems analysis; nitrogen budgets; integrated assessment; stakeholder dialogue and communication; and best management practices;

(g) Measures considered as "best management practices" for abating emissions and mitigating impacts are based on the above-mentioned principles, dimensions and tools. Measures are often site- and region-specific and so represent a menu of options from which coherent packages of actions can be constructed.

144. The following recommendations can be made concerning the principles of integrated sustainable nitrogen management:

(a) Measures for integrated sustainable nitrogen management should be based on the dimensions, principles and tools outlined in the present chapter;

(b) Integrated sustainable nitrogen management is needed to help achieve multiple Sustainable Development Goals, including those related to human health, food, water, climate and biodiversity;

(c) Though farmers are the main N managers on the ground, and also bear many of the costs and reap some of the benefits of N emission-abatement measures, all societal actors in the food production-consumption chain, including policymakers and citizens, should take responsibility for achieving integrated sustainable nitrogen management, with fair remuneration for nitrogen managers.

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