Chapter VI: Land-use and landscape management

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A. Introduction and background

382. The overarching assumption of this chapter is the challenge of mitigating the environmental impact of nitrogen (N) use while keeping its benefits for production of crops and livestock. This requires the implementation of measures at the landscape scale that facilitate removal of reactive nitrogen (N_r) from water and air, thereby preventing N cascading along hydrological and atmospheric pathways.

383. This chapter reviews a range of land-use and landscape management practices, and how they can contribute to a more sustainable use of N for agricultural production, while mitigating the negative effects of reactive N_r in the environment. Key elements are summarized to provide guidance on integrated sustainable nitrogen management, taking into account air, water and climate co-benefits.

384. This chapter integrates knowledge from the previous chapters of this guidance document, including livestock and arable production systems measures at the landscape scale. Measures include use of land adjacent to agricultural production areas, and thereby add the benefits of a whole-landscape approach to the principles of sustainable N management (chapter III).

B. Why consider land-use and landscape level management?

385. Adaptation of land-use and landscape level management practices are necessary to optimize use of Nr, whilst mitigating unwanted effects of N_r pollution on air, water or climate. Some of the advantages of landscape management and measures and territorial management are set out below:

(a) Landscape management enables N_r pollution problems to be addressed exactly where they appear, both in space and time, which helps to achieve the desired N mitigation effect;

(b) Landscape measures can be economically favourable compared to other types of measures (see chapters IV and V). They can also be placed outside agricultural areas, retaining agricultural production, while creating new nature and recreational resources in the form of hedgerows, forests, extensive buffer-zones around fields, streams, or wetlands;

(c) Territorial management could help to maximize circular economy by optimally distributing the available fertilizer resources, improving the application of circular economy principles, and integrating knowledge on local resources.

386. As summarized in box VI.1 and the section below, strategic land-use changes and landscape level management practices have benefits via a combination of environmental and economic effects, as a result of physical/chemical, biological and socioeconomic factors.

C. Land-use and landscape management effects in practice

387. In this section, the active use of landscape management for N_r effects mitigation is illustrated using the following examples:

(a) Mitigation/abatement of NH_3 emission hot spots from livestock houses and slurry tanks by planting trees downwind of the source area, to adsorb NH_3 and disperse it vertically;

(b) Planting vegetation around protected nature areas or along streams, to intercept N_r (for example, in the form of airborne NH_3 or leaching of NO_3^- to surface waters) before reaching the protected natural areas, which are often vulnerable to N_r pollution;

(c) Strategic establishment of wetlands to clean/treat water polluted with nitrates and dissolved organic N from field drains or dikes via denitrification and sedimentation before it reaches vulnerable surface waters;

(d) Spatio-temporal timing of grassland management and manure distribution to minimize N-losses in vulnerable areas or times of the year (for example, in dedicated groundwater protection areas);

(e) Adaption of N_r fertilization schemes (fertilizer types, nitrification and urease inhibitors, timing of fertilizer application) depending on the distribution of soil, subsoil and geology across a landscape;

(f) Reduction of N fertilization, and changes in management practice to reduce the nitrate losses to vulnerable surface waters and groundwater in geographically targeted areas with a low N retention potential of the subsurface.

388. One of the major challenges in the shift towards more geographically targeted, landscape level N_r measures is the knowledge and documentation of their effects.

Box VI.1: Definition of landscape and land-use management practices for nitrogen mitigation.

Landscape can be defined as a delineated geographical area integrating all types of land-use and management practices, which includes effects on the N cycle and related emissions.

The typical view of a landscape is of a composite of land-uses seen altogether, typically from a few to several tens of square kilometres. Landscape areas may be defined according to many criteria, such as a mix of land ownership and land-use, a watershed or a legally defined administrative area. The idea of such a landscape is illustrated by figure VI.1.

The main focus here is the N_r-related management of agricultural (including livestock facilities) and forest land in rural landscapes. Urban land-use and infrastructure are relevant for other landscapes but are not the focus of this chapter.

Landscape measures are sometimes employed in situations where applicable measures designed to reduce the input of N_r to the rural environment have already been implemented, and where socioeconomic factors argue for the retention of activities, which, however, are the source of N_r pollution, typically from agriculture. In terms of pollution, mitigation is here taken to mean "reducing the adverse effect" of any N_r compound such as the atmospheric pollutant ammonia (NH_3), the aquatic pollutant nitrate (NO_3^-), or the greenhouse gas nitrous oxide (N_2O). The term "abatement" is here taken to mean "reducing the loss to the environment" of such N_r compounds and dinitrogen (N_2). In general, landscape measures are primarily mitigation, rather than abatement, strategies. This is to say that they provide an additional means to reduce specific adverse effects in the environment, which is typically larger than their effect on reducing overall losses to the environment.

This conclusion was also reached in the European Union-funded integrated research project NitroEurope[29], where pilot research studies were carried out in six European case landscapes (for example, Dalgaard and others, 2012); as further described in the European Nitrogen Assessment (Cellier and others, 2011; Sutton and others, 2011), which included experiences from key national research projects in France, Denmark, the Netherlands, Scotland (United Kingdom of Great Britain and Northern Ireland) and other countries with different climatic conditions. Based on these studies, Cellier and others (2011) concluded that, at field or farm scales, processes of N transformation and transfer have been extensively studied and have provided a fair insight into the fate of N at restricted spatio-temporal scales, even though the majority of studies are from North-Western Europe.

389. Reactive nitrogen cannot be addressed as a single environmental pressure due to the cumulative effects of land-use and climate change processing of nitrogen. Leaching of N_r reflects non-linear interactions, so that it is threshold-dependent and interlinked with acute stressors. Treating these stressors in isolation, or in a simplified additive manner, may seriously underestimate future N-related risks, including eutrophication, acidification, greenhouse gas emissions and biodiversity change, as well as changes in the functioning of forest, natural land and water systems.

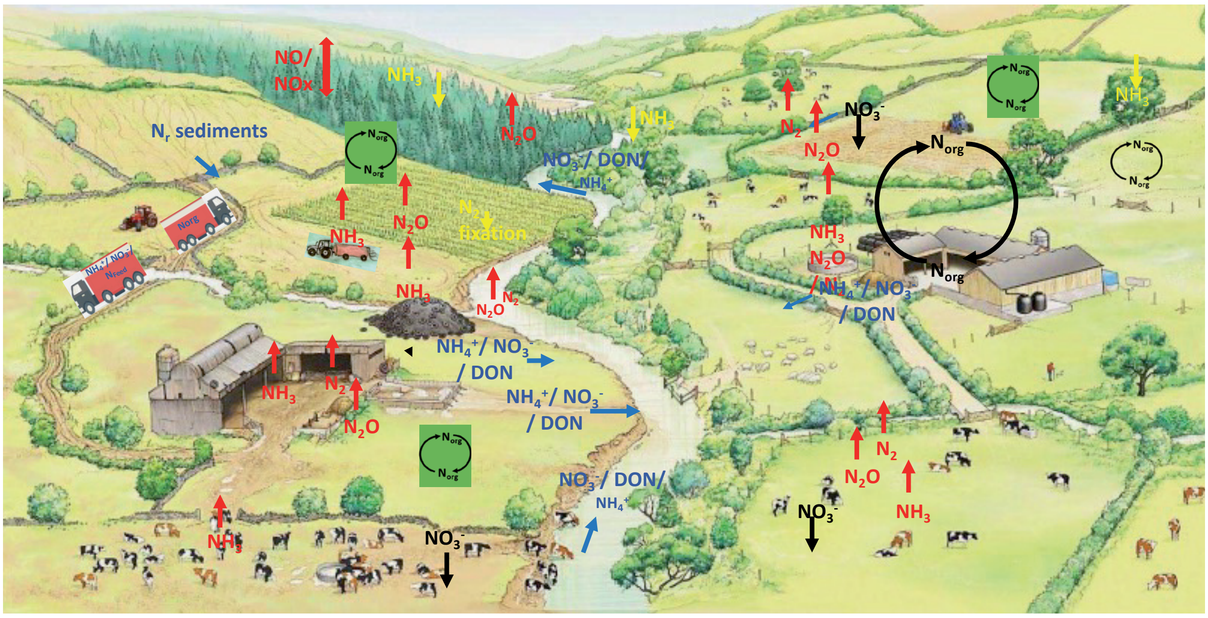
390. Reactive nitrogen cascades along hydrological and atmospheric pathways at a range of scales, from landscape to regional scales. N_r can be transferred by a variety of pathways in significant amounts from their sources to the recipient ecosystems (see figure VI.1). For example, gaseous NH_3 emitted from animal housing or a field can be redeposited to the foliage of nearby ecosystems in amounts that increase the closer the source is horizontally to the recipient ecosystem and vertically to the soil surface (Fowler and others, 1998; Loubet and others, 2006). Similarly, wetlands or crops/grasslands at the bottom of slopes can intercept NO_3^- in the groundwater that originates from N applied further up the slope, due to a lateral flow of water at landscape scales (Casal and others, 2019). In both cases, this can lead to large inputs of N_r to the receptor ecosystem that may have potential impacts on the ecosystem function (Pitcairn and others, 2003). This increases the risk of enhanced N_2O and NO_x emission (Beaujouan and others, 2001; Skiba and others, 2006; Pilegaard and others, 2006), pointing to the need for integrated N management and assessment beyond the field scale (Quemada and others, 2020). Without immobilization of N_r in biomass or its removal via denitrification, lateral losses of N_r continue along the N cascade (Galloway and others, 2003; Billen and others, 2013) (see figure VI.1).

391. These N_r emissions resulting from N_r transfer from source to receptor ecosystem are often termed "indirect emissions" and represent a significant fraction of total soil N_2O and NO_x emissions, although their magnitude is still debated (Mosier and others, 1998; Liu and Greaver, 2009, Tian and others, 2019). The inclusion of uncultivated or marginal areas that are outside or peripheral to the agricultural systems is important for understanding flows and budgets of energy and matter, including N, which emphasizes the need to adopt a landscape perspective.

392. Livestock are a major source of N_r pollution, specifically in regions with high livestock densities (Leip and others, 2015), but can provide services that are valued by society, such as habitat provisioning or being part of cultural and natural heritage (Dumont and others, 2017). Some countries that have intensive livestock production in close proximity to sensitive ecosystems have already imposed a range of measures to reduce N_r pollution (for example, the Netherlands, Denmark), but still have difficulty complying

29 https://www.peer.eu/projects/peer-flagship-projects/nitroeurope/.

Figure VI.1: Simplified overview of landscape N_r flows showing source and sink functions of landscape elements such as farm buildings, fields, forests, pasture etc. for various N_r forms



Source: This figure from http://www.westcountryrivers.co.uk has been modified on basis of the Creative Common License https://creativecommons.org/licenses/by-nc-sa/4.0/.

Note: Major N_r sinks and sources are highlighted in the form of gaseous N_r flows (red for sources, yellow for sinks), N_r flows to and in surface waters (blue arrows, including sediment erosion and surface run-off), nitrate leaching to groundwater (black arrows) and changes in soil organic N pools (green squares with black arrows). The fixation of atmospheric N and the deposition of atmospheric ammonia (NH_3) is indicated (yellow arrow) together with the import and export in products to and from the landscape (trucks providing feed and fertilizer, and export of manures, crops, livestock and animal products). Major flows to air include NH_3, nitrogen oxides (NO_x)[30], nitrous oxide (N_2O) and dinitrogen (N_2). Major flows to water include nitrates (NO_3^-), ammonium (NH_4^+) and dissolved organic nitrogen (DON). Organic nitrogen (N_{org}) balance in soils is also considered. Of most importance for air quality, ecosystems and health are emissions of NH_3 (mainly from livestock wastes and chemical fertilizers) and NO_x (which is emitted from agricultural soils and N-saturated forests mainly in the form of NO, reacting to form NO_2, in addition to NO_x from traffic sources).

with requirements of European Union legislation such as the Water Framework Directive, the Habitats Directive and the National Emission Ceilings Directive. With the most cost-effective measures to reduce Nr losses at source already implemented, there has therefore been increased interest in measures at landscape level (Dalgaard and others, 2012, 2016; Jacobsen and Hansen, 2016).

D. Main issues for the reduction of reactive nitrogen emissions via land-use and landscape management

1. Nitrogen flows in the rural landscape

393. Figure VI.1 provides an overview of N_r flows, sinks and sources in rural landscapes, and the cascade of reactions from N_r input in the form of fertilizers and feed, through the cropping and livestock system, and to the natural ecosystems, also put forward in the European Nitrogen Assessment by Sutton and others (2011). It is especially the N_r flows to and from the natural/semi-natural ecosystems, and from the farms and field to the aquatic ecosystems that are targeted by the landscape level measures exemplified above. These flows can be divided into those relating to: air pollution, including greenhouse gas (GHG) emissions (see figure VI.3); surface- and groundwater pollution (see figure VI.2); and sources and sinks of nitrogen (see figure VI.1). Each of these flows is described in the sections below.

2. Guiding principles

394. Rural environments have a range of stakeholders relevant to mitigation and abatement of N_r pollution using landscape measures (for example, farmers and other land managers, conservation agencies, regional government, other businesses, civil society organizations and citizens). Their involvement can help identify barriers to the effective implementation of measures, how these barriers can be avoided, and how to encourage the development of a consensus that lends the measures political and social legitimacy. According to Andersen and others (2019), guidance for land-use and landscape management to mitigate N pollution can be defined in two steps:

30 See footnote 2.

(a) **Step 1: Mapping of the present situation** (for example, current land-use, soil and geological properties, water flows) to understand the N cascade in the landscape, mapping of N management practices, as well as identifying relevant stakeholders and their targets for reduced N_r pollution. This can benefit from locally held workshops (involving farmers scientists, politicians, local stakeholders and other interest groups) to identify suitable approaches and measures for reducing landscape N loading. It is also important to collect relevant landscape-scale data, which can be relevant to publicly available policy targets for (reduced) impacts of N in the area. Each actor in the landscape can thereby gain an overview of the possibilities for action, both within the farming system and in the context of the whole landscape;

(b) **Step 2: Selection and prioritization of land-use and landscape management solutions to reach reduction targets**. These solutions are, in the first instance, influenced by geophysical constraints, which are rather difficult to overcome. However, other environmental and socio-economic goals of stakeholders/actors also need to be considered.

395. In this approach, each stakeholder/actor in the landscape may be provided with a list of measures as a basis for discussions and decisions, together with information on their potential environmental and economic effects at the farm and landscape scale. A hypothetical example could be a multi-actor discussion on the placement of a small wetland along a stream running through a farm. The wetland promotes the removal of N_r from upstream N_r sources via uptake into plant biomass and by denitrification to N_2, as far as possible avoiding N_2O emissions (Vymazal, 2017; Audet and others, 2020). Such upstream catchment management may cover both fields within an individual farm and the fields of other farms. Moreover, wetlands provide additional ecosystem services, for example, in the form of increased biodiversity, flood protection and scope for leisure activities such as fishing. Key risks in this example include the possibility of increased N_2O emission through denitrification and the loss of N_r resource from the farming system.

396. The integration of key stakeholders into both steps of the process is important to facilitate development towards the design of landscape measures, management and use, which minimizes N_r cascading and losses, while sustaining its landscape productivity. This process will normally require iterative repetitions of the above-mentioned two steps, to allow the consequences of different scenarios to be calculated. This also allows participants time for reflection and consultation with other members of their stakeholder groups.

397. The landscape illustrated in figure VI.1 includes the following major compartments:

(a) Farms; including livestock houses, manure and fodder storage, grazed grasslands, arable and grasslands fertilized with manure or mineral forms of N, permanent crops and rotations with and without tillage;

(b) Forests and other semi-natural systems in the form of hedgerows, small biotopes with woodlands, ponds etc., and more or less permanently set-aside agricultural land; and

(c) Aquatic ecosystems, such as ponds, lakes, streams and wetlands. These systems are fed by direct run-off, field-drains or groundwater. (The water system is illustrated in more detail in figure VI.2).

398. Depending on the characteristics of a given landscape, and the most urgent issues that require attention, a different priority order might be given to address N_r pollution of water, air, soil or climate impacts. For instance, in dry Mediterranean climates, like in Spain, impacts on air pollution may, for health reasons, be addressed first (for example, where respiratory diseases are frequent), whereas for a landscape situated in the wet coastal climate of Denmark, N_r impacts on water quality might be of highest priority (for example, where legally binding limits for vulnerable estuaries and coastal water quality are exceeded, Dalgaard and others, 2014).

399. The effects of measures to reach one target (for example, for water) also often affect targets related to air, soil and climate. The same is the case for measures aimed at improving air and soil quality, which typically directly or indirectly also affect GHG emissions. This means that, in a situation where water is prioritized first, measures to reach the reduction targets set for the surface and groundwater would need to be defined first (primarily for nitrates, but possibly also for dissolved organic carbon). Subsequently, measures to reach air pollution reduction targets might follow (primarily for NH_3, and possibly also for NO_x). Finally, targets and measures might need to be identified and implemented for soil protection (and thereby rates for the build-up of soil N and organic carbon (C) stocks, or prevention of soil organic C and N mining), as well as reductions in net GHG emissions (here net balance of CO_2, N_2O and CH_4 fluxes in terms of CO_2 equivalents). Such an approach requires consideration of the GHG emissions from soils, as well as from other sources like manure storages, livestock and livestock houses, both in the form of nitrogen compounds (primarily N_2O) and carbon compounds related to the nitrogen cycle (primarily CO_2, but possibly also CH_4; Dalgaard and others, 2015).

E. Integrating aspects of water, soil, air and climate impacts

400. In accordance with figure VI.1, the two main categories of N_r pollution are via water (mainly NO_3^- but also other N_r forms, including organic N compounds) or air (mainly NH_3, N_2O and NO_x and N_2). Although N_2 is not a pollutant, its loss is accompanied by reduced nitrogen use efficiency for crop production, thus requiring increased N_r inputs. Consequently, the emission of N_2 can be considered as representing an indirect form of nitrogen pollution. Understanding the different local conditions for these types of losses is important when prioritizing landscape mitigation measures following the above-mentioned guiding principles.

401. In the following two sections, the main pollutants are presented, showing how mitigation options for surface and groundwater pollution are linked to local soils, geology and geomorphology (first part), whereas mitigation options for GHG emissions are closely linked to air pollution (second part). When integrating the combined effects of N_r mitigation options for water, soil, air and climate impacts, it is important to assess all sources/sinks in the landscape together, as the potential mitigation options depend on landscape heterogeneity and the scale at which the mitigation options are carried out. This is discussed in a following third section.

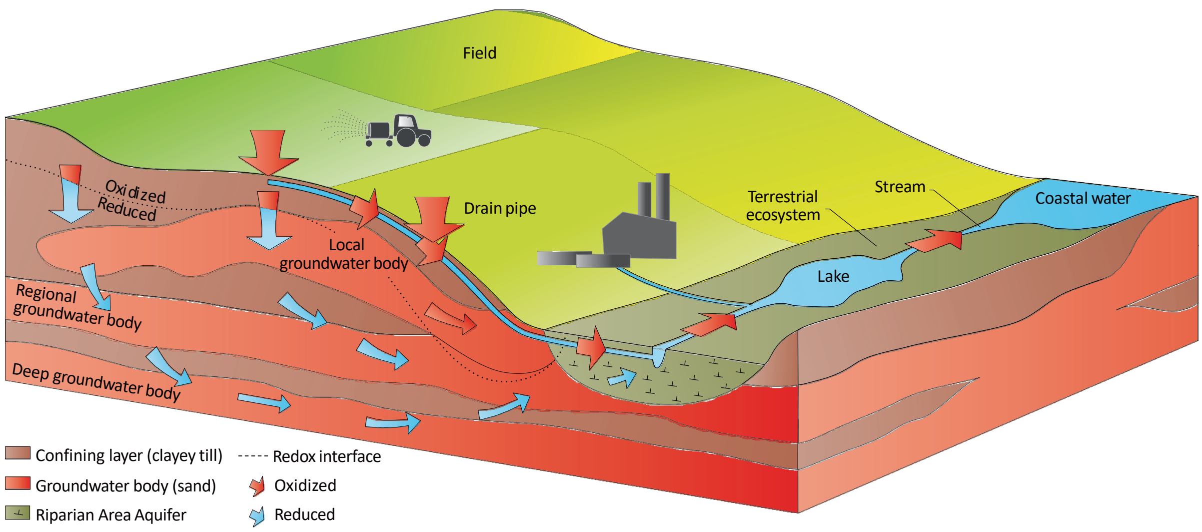
1. Surface and groundwater pollution, soil and geology

402. Nitrogen in water can be mapped in the form of concentrations of NO_3^-, NH_4^+ and DON in surface waters (streams, lakes and coastal waters) and in groundwater reservoirs, with concentrations being closely linked to N_r inputs, flows and removal in a given landscape (see figure VI.2). Based on this assessment, landscape-specific targets for ground- and surface-water quality can be set. Within the European Union, this must correspond to the related standards set from the objectives and targets of the Water Framework Directive, the Nitrates Directive and the Drinking Water Directive (good ecological and chemical status, reducing and preventing pollution of water by nitrates of agricultural origin). For example, the European Union Groundwater Directive[31] sets a groundwater quality standard of 50 mg of nitrate per litre, corresponding to the standard for the content of nitrate in drinking water according to the Drinking Water Directive. For other parts of the UNECE region, the World Health Organization (WHO) also applies a maximum of 50 mg of nitrates per litre for drinking water (see also the European Commission, 2019). From such information, and information on possible measures (see sections below), scenarios can be constructed that include land-use and landscape management practices to meet these targets (Hashemi and others, 2018a, 2018b).

2. Air pollution and related greenhouse gas emissions

403. On the basis of current agricultural practices, emissions of N_r to the air can be measured and/or estimated via modelling (as exemplified in figure VI.3), and compared to possible "critical loads" for atmospheric Nr deposition. Critical loads are deposition limits below which adverse effects are not known to occur according to present knowledge. The impact of agricultural developments on the exceedance of Nr critical loads for sensitive nature areas within or nearby the landscape should also be considered (Dragosits and others, 2006). From this, measures to reach reduction targets for, for example, NH_3 volatilization, can be defined. In addition, such an approach allows the identification of regional N_r pollution hot spots (see figure VI.3) and to estimate abatement/mitigation potential for emission of the greenhouse gas N_2O and other GHGs (see figure VI.3).

Figure VI.2: Conceptual model of the interaction of shallow groundwater bodies with dependent aquatic ecosystems



Source: Based on Hinsby and others, 2008.

Note: The transport pathways to the aquatic ecosystems are indicated by arrows. The blue arrows symbolize reduced groundwater (below the redox zone) and the red arrows symbolize water flows in the upper oxidized zone.

31 Directive 2006/118/EC of the European Parliament and of the Council of 12 December 2006 on the protection of groundwater against pollution and deterioration, *Official Journal of the European Union*, L 372 (2006), pp. 19–31.

3. Sinks and source heterogeneity and scale issues

404. Water, air and greenhouse gas pollution within a landscape depend on both sinks and sources of nitrogen, and on the specific farm systems within the landscape, as agricultural systems are the dominating source for nitrogen pollution.

405. Figure VI.4 provides an example of N_r sources and sinks in dependence of farm types. It illustrates that different types of production systems are associated with different types of environmental N_r losses, estimated by the www.farm-n.dk/ model. For example, leaching of NO_3^- is found to be the dominant form of N_r loss for cash crop farms in this context, and, to some degree also, for granivore production systems (for example, pig and poultry production farms). Conversely, in absolute values the leaching per hectare is higher for livestock as compared to cash crop farms in this context. Cattle (ruminant) production systems can have relatively low N_r leaching losses, depending on intensity and management practices, although such production systems show high NH_3 emissions, associated with animal housing, manure storage and spreading. In particular, intensive dairy production systems involve substantial N inputs with substantial NH_3 emissions. In cool oceanic climates, extensive grazing of beef cattle all year round can be associated with low NH_3 emissions (due to effective urine infiltration compared with livestock manures), though may still risk increased NO_3^- leaching, N_2O, NO_x and N_2 emission.

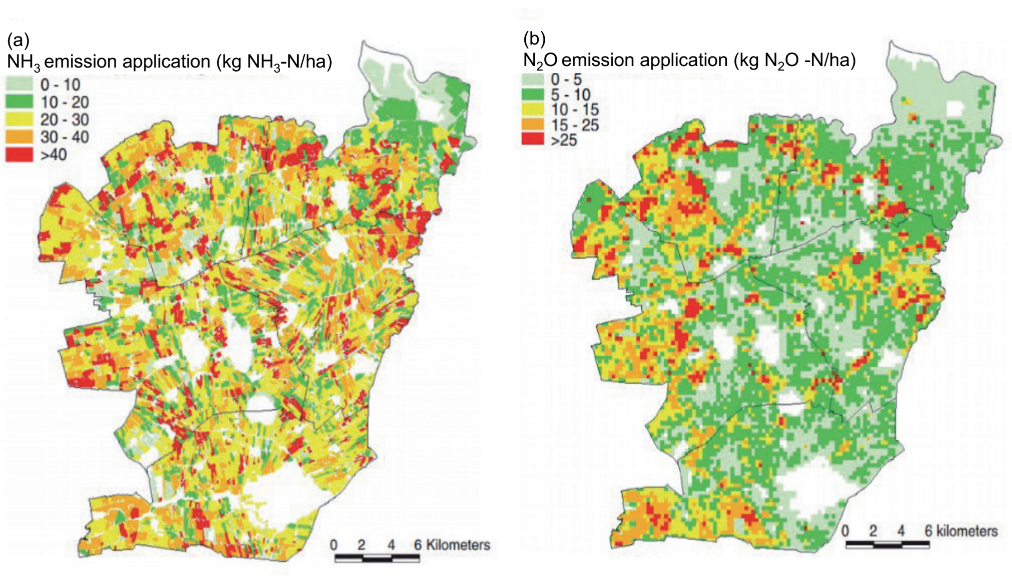
406. Other effects associated with manure management are changes in soil N stocks (and also soil C stocks) as a result of manures applied to pastures and cropland. In the study by Dalgaard and others (2011), the estimated increase in soil N stocks is highest for the ruminant systems (with relatively more grasslands and intensive use of manure, including straw in deep bedding etc., and manure applications to grass- and croplands). In contrast, cash crop systems, which do not receive manure applications, showed a net reduction in nitrogen (and carbon) stocks when manure addition was not included in this system.

407. The huge difference in environmental N_r loss pathways for different farming systems, and thereby in agricultural N_r sources and sinks within the landscape, means that the geographical position of a farm matters with regard to environmental N_r losses to sensitive water bodies or sensitive terrestrial nature areas. This source-sink relationship is also influenced by variations in geopedomorphological characteristics, which affect rates of leaching losses, surface N_r losses, lateral transport of N_r in soils and parent material (see figure VI.2). Consequently, appropriate planning of land-use, land management, placement of farms, etc., will have a significant effect on landscape N_r fluxes, offering an opportunity to reduce N_r loads at landscape scales.

408. Landscape measure might include: choosing a location for (new) livestock production facilities that is further away from sensitive ecosystems; incorporation of certain land-use types (for example, planting trees around livestock facilities, buffer zones around water bodies, and placement of N_r reducing wetlands, etc.); and cropping systems with different intensity (for example, grassland versus rotational land). Altering the rates of application and distribution of manure and manufactured inorganic fertilizers according to local sensitivity within the landscape (or even in and out of the landscape) provides another option that can help to reach N_r mitigation and abatement targets. Such targeted land-use and management practices can thereby be used as measures to help fulfil reduction targets for water-, air- and GHG-related N_r emissions.

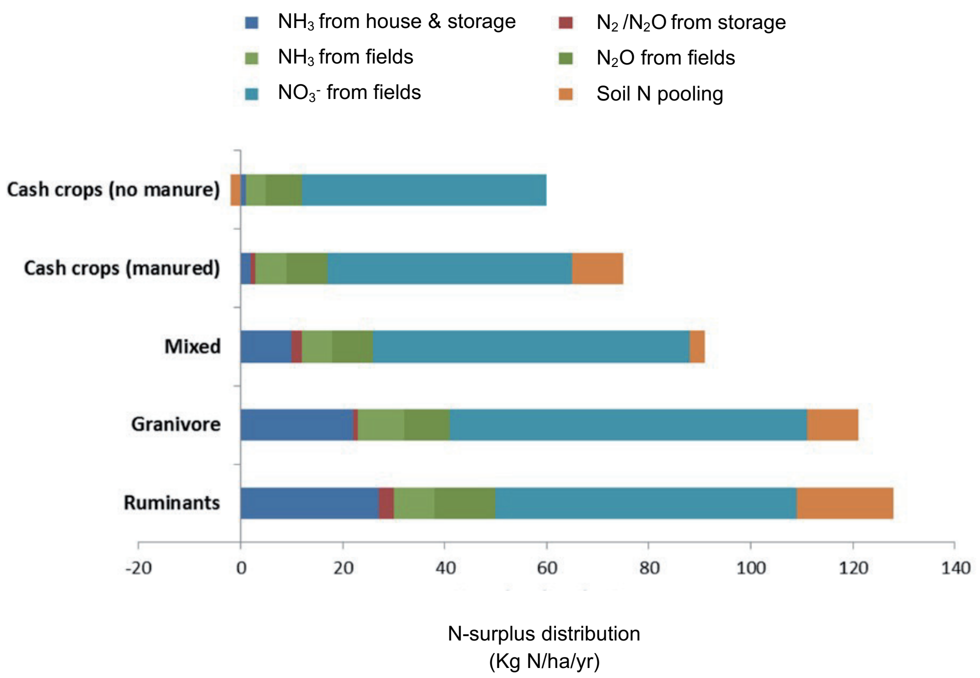
409. It should be remembered that N_r at site or landscape scale is a valuable resource for crop, biomass and livestock production. Recycling of all N_r resources should therefore be

Figure VI.3: Example of annual emissions of ammonia from manure application (a) and total nitrous oxide emissions from soils (b) in a rural landscape of the Netherlands



Source: From Cellier and others, 2011.

Figure VI.4: Distribution of nitrogen surplus between types of Nr losses and pools, compared for five different agricultural systems within a Danish landscape



Source: Based on Dalgaard and others, 2011, estimated using the www.farm-n.dk/ model.

Note: Losses of N_2, NO_x and organic N from soils were not estimated in this study. For cash crop farms with no manure, a net N emission from soil N pools was estimated, while for the other farming system, a net build-up of soil N was estimated, thereby reducing the N_r emission for the year accounted.

prioritized. For example, biomass produced with the support of N_r recaptured in the landscape, such as paludal biomass in wetland areas or trees grown in the vicinity of livestock production, should be evaluated as bioenergy resources. This means that it is important not only to keep account of direct losses of N_r pollution, but also of the amount of N_r lost as N_2. This emphasizes the need to develop holistic assessments to quantify all N_r flows at landscape scales.

410. Flows and transformations of N_r within a landscape are determined by the topography and spatial variability of the biogeochemical and physical characteristics of the soil. These, together with climate and agricultural N management, determine soil microbial N cycling (with specific emphasis on nitrification and denitrification processes), plant-soil N interactions, and, thus, fluxes of NH_3, NO_x, N_2O, N_2 to the atmosphere and the leaching of dissolved organic N (Salazar and others, 2019) and NO_3^- to the rivers and other aqueous bodies (see figures VI.1 and VI.2). In order to assess such N_r flows at landscape scale, it is important to gather information on field scale/farm scale "activities", such as agronomic management, fertilizer type, N application rates, soil types and topography and emission-abatement and mitigation approaches. New technologies, for example, drones, satellites and aircraft, are valuable tools to support relevant data collection (for example, soil moisture, topography, vegetation types). An example is the use of satellite vegetation maps to estimate landscape scale CH_4 fluxes (Dinsmore and others, 2017), which can inform the development of abatement strategies.

F. Priorities for policymakers

411. In general, recommendations for policymakers[32] follow the above-mentioned guidance principles, based on assessment of the present situation (Step 1: Mapping of the present situation) as a background for defining suitable land-use and landscape measures (Step 2: Selection and prioritization of land-use and landscape management solutions to reach reduction targets). This can provide a prioritized order of measures to fulfil targets set for (the reduction of) water, air, soil and climate impacts.

412. In line with the guidelines of the European Commission (2010), when designing policies for the implementation of such measures, it is recommended that, prior to implementing measures, their effects be assessed (*ex ante* assessment), and that the economic costs of measures be

[32] Policymakers are considered in this section to include all kinds of representatives from central agencies (agricultural, environmental, finance, health, trade), leaders in food industry and agriculture, scientists, extension services and regions around the world (for example the UNECE regions, including North America, the Eastern Europe, the Caucasus and Central Asia region, the European Union, smaller administrative regions within countries, municipalities, watershed regions, etc.).

included and considered. Moreover, after a defined period of implementation, it is recommended that a corresponding assessment of their effectiveness in practice be carried out (*ex post* assessment). The second assessment might be used to revise policies, and to implement iteratively new additional measures on the basis of the above-outlined two-step approach. An example of such an iterative policy cycle is reported for the five subsequent national Danish Nitrogen Action Plans 1987–2015, which included both *ex ante* and *ex post* assessments of the costs of these action plans (Dalgaard and others, 2014).

413. Over the last five years, there has been increased emphasis on N_r measures, which contribute to a more circular bioeconomy, allowing the costs of measures to be offset by new revenue opportunities from recaptured N_r (for example, Dalgaard and others, 2014; Sutton and others, 2019). Relevant measures include those that help to use nitrogen more efficiently, such as the use of manures in biogas facilities, which, apart from making the N_r more readily available for plants, can also serve as distribution centres for a more optimal distribution of fertilizers recovered from organic materials (chapter IV) in a landscape or region. Other examples include:

(a) Use of N_r in locally grown protein from green biomass in biorefineries;

(b) Use of green manure in biogas plants, including N_r recovery;

(c) Use of crops for energy with N_r recovery;

(d) Use of mixed farming to increase overall landscape nitrogen use efficiency and N_r recovery (Wilkins and others, 2008);

(e) Agroforestry systems to maximize recovery of N_r already released to the landscape.

414. Such options may also lead to production systems that are more resilient to climate change and with more diverse services delivered, as well as having reduced N_r footprint. For example, woodlands in landscapes serve many functions, such as increasing landscape water retention to reduce flooding, provision of wildlife habitats and provision of shelter for livestock, where the potential to use them as N_r management tools is just one opportunity (for example, Sutton and others, 2004).

415. In this context, it is important to carry out both a N_r budget- and an economic/welfare impact assessment of the measures (for example, not only the environmental, but also the economic impacts for farming versus the wider socioeconomic impacts).

G. Land-use and landscape mitigation measures

416. The estimated effects of landscape measures as part of sustainable nitrogen management are summarized below according to five main categories. The landscape measures listed below provide options for consideration in steps 1 and 2 (for example, mapping of present situation, and selection of management solutions), which can then be selected and prioritized according to local context:

(a) Land-use measures for mitigation of N_r effects from crops and crop rotations;

(b) Landscape measures for mitigation of N_r effects from management of riparian areas and waters;

(c) Afforestation, set-aside and hedgerows as measures to mitigate N_r effects;

(d) Mitigating the cascade of N_r effects from livestock hot spots;

(e) Smart landscape farming in relation to mitigation of N_r effects.

417. Following the description of each measure below, a table (see tables VI.1–VI.16) summarizes the UNECE category for effectiveness/practicality of implementation (following the approach of ECE/EB.AIR/120, Bittman and others, 2014), and the magnitude of effect of each measure[33]. Expert judgement is used for ammonia volatilization, denitrification losses as N_2O, NO_x and N_2, run-off and leaching losses as NO_3^-, and overall total N losses.

418. In the present chapter on land-use and landscape scale measures, the primary focus is on mitigation of adverse impacts, though there can also be benefits for emissions abatement.

419. Where a measure is considered to result in an increase in losses of a specific nitrogen form, it is, by definition, also assigned to category 3 for that nitrogen form. The magnitude of effect can be considered as an indication of "effectiveness" of the measure as distinct from the extent to which the measure is "applicable" in different contexts. Where clarification is necessary, magnitude of effect of a measure is described in comparison to a specified reference system. For example, in the case of constructed wetlands, two reference systems are specified:

(a) Taking no action (with polluted water lost directly to streams and rivers); and

(b) Advanced processes focused on nutrient recovery.

420. In some parts of the UNECE region, use of certain reference systems may be prohibited, for example, because of the associated pollution levels. Table VI.17 provides an overview of all the land-use and landscape management practices and the expected effects in relation to leaching/run-off (water pollution), NH_3 volatilization (air pollution) and other gaseous N emissions including N_2O emissions (climate impact), and the overall effect on N pollution.

1. Measures specific to placement of crops and crop rotations

421. The main effect of optimized selection of crops and sequences of crops (crop rotations) is to improve the uptake of nitrogen from the roots and thereby reduce the leaching of nitrate in a geographically targeted way, with minor direct effects on other N compounds. This can in general be

33 See chapter I, paras. 16–20, for a description of the UNECE categories and system for representing the magnitude of effect.

achieved through the measures listed below:

Landscape Measure 1: Increasing land cover with perennial crops

422. Introducing perennial crops, such as grasslands, predominately grass or grass-clover mixtures, can reduce the risk of environmental N_r losses due to N_r immobilization in plant biomass and litter. It also increases soil N (and C) stocks, with higher soil organic carbon contents providing increased N_r retention capacities. This reduces the risk of N_r leaching, but could potentially increase the risk of higher soil N_2O emissions. However, in most studies, increases in N_2O emissions were found to be insignificant (Li and others, 2005; Abdalla and others, 2019).

Table VI.I: Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Landscape Measure 1

Nitrogen form	NH_3	N_2O	NO_x	NO_3^-	N_2	*Overall N Loss*
UNECE Category	3	2	3	1	3	1
Magnitude of Effect	~	↓↑	?[a]	↓↓	↓↑	↓

[a] Insufficient data to estimate the effect, though responses may be similar to N_2O and N_2.

Landscape Measure 2: Use of cover crops in arable rotations

423. Introducing cover crops (sometimes called "catch crops") following the main crop will help to reduce nitrate leaching (Gabriel and others, 2012). Such crops can be placed strategically in a landscape at target locations to reduce nitrate run-off. Nitrate originating from post-harvest decomposition and mineralization is taken up by cover crops between the main cropping season. Cover crops also help reduce the risk of soil surface fluxes (erosion) and surface sediment and N_r transport to streams. At the start of the new growing season, cover crops are ploughed into the soil (for example, as "green manure"), and provide additional organic matter and nutrients to the subsequent crop, which can be especially beneficial in intensively cultivated Mediterranean conditions (Karyoti and others, 2018). Under continental conditions, Lukin and others (2014) found that growing a crop of oil radish after solid manure or slurry application led to substantially reduced losses to groundwater of both ammonium and nitrate, as well as for phosphorus and potassium.

424. Winter cover crops are used in some circumstances to minimize soil mineral N concentrations over the high-risk period for nitrate leaching, but their success in increasing N use efficiency over the whole cropping cycle depends on effective management of the cover crop residue and appropriate amendment to the fertilization of the subsequent crop. Most importantly, the cover crops must be planted early so they are well-established before the high-risk period.

425. Incorporation of cover crops is beneficial for increasing soil C and N stocks, but bears the risk of increased soil NH_3, N_2O and NO_x emissions associated with mineralization following the incorporation of the cover crops into the soil (Sanz-Cobena and others, 2014; Xia and others, 2018; Abdalla and others, 2019). An integrated management of cover crops adapted to local conditions can maximize agroenvironmental benefits while reducing trade-offs (Tribuillois and others 2016, Quemada and others, 2020). In colder climates, freeze-thaw cycles over the winter period can cause significant nutrient release and N_2O emissions (Wagner-Riddle and others, 2017). In order to minimize N loss, it is necessary to time

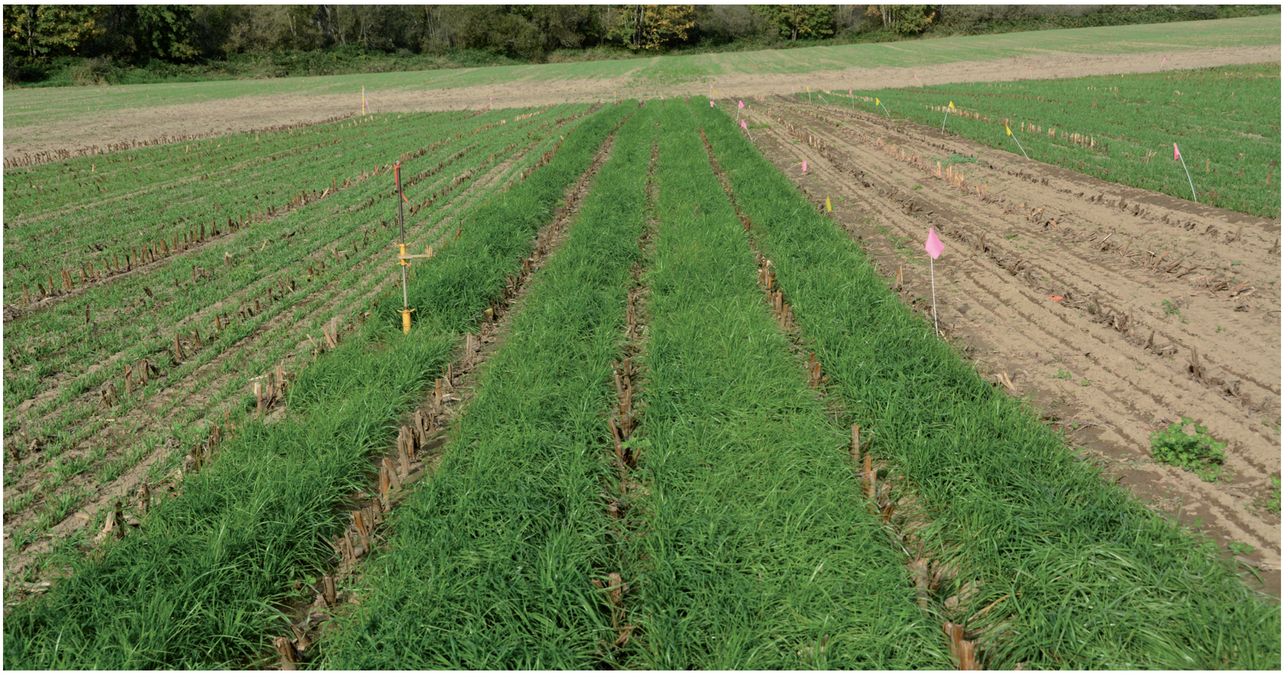


Image 25: Inclusion of cover crops in arable systems (Landscape Measure 2) protects the soil and utilizes mineralized nitrogen reducing winter-time nitrate and other nitrogen losses. In this example a 'relay crop' of Italian ryegrass is sown under maize so that the grass is already established when the maize is harvested (photograph: © Shabtai Bittman).

tillage operations in order to optimize synchrony between N release and uptake by the subsequent crop. Where there is an N surplus, cover crops will not mitigate losses unless they displace imported N (for example, reducing N inputs to compensate N savings; principle 6).

Table VI.2: Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Landscape Measure 2

Nitrogen form	*NH_3*	*N_2O*	*NO_x*	*NO_3^-*	*N_2*	*Overall N Loss*
UNECE Category	3	2[a]	2	1	2[a]	1
Magnitude of Effect	~	↓↑	↓↑	↓	↓~↑	↓

[a] Denitrification losses are assigned to category 2 because these may be increased following the incorporation of the cover crop/ residue. The timing of this operation will typically be in spring after the drainage season, so that there is no significant risk of increased leaching. It is expected that leaching will be greatly decreased because any surplus N at the end of the previous season will have been taken up by the cover crop over the risk period.

Image 26: Illustration of intercropping between grain and legume (narrow-leaved vetch, *Vicia sativa*, plus triticale, *Triticosecale*) (photograph © Sergei Lukin, 2021).

Landscape Measure 3: Inclusion of N_2-fixing plants in crop rotations (including intercropping)

426. Including N_2 fixing crops like legumes (for example, beans, lentils, etc.) in crop rotations allows N fertilizer application rates to be reduced. Under this approach, N_2 is reduced to NH_3, which is then assimilated into organic nitrogen compounds by bacteria associated with root nodules of the legume. This organic N_r becomes available to following crops by incorporation of crop residues. Legumes stimulate increases in soil C and N and are expected to have an overall beneficial effect in reducing nitrate leaching in comparison with the use of chemical fertilizers (Voisin and others, 2014; Jensen and others, 2020). The anticipated mechanism is that biological nitrogen fixation acts as a "slow-release" form of N_r provision, which proceeds according to the needs of plants (cf. Drinkwater and others, 1998). It has been suggested that adverse stimulating effects on N_2O emissions are possible, but not likely (Abdalla and others, 2019). By contrast, as with Landscape Measure 3, incorporation of legumes into the soil leads to a pulse of mineralization. While this can help satisfy the N needs of the subsequent crop, this mineralization pulse also risks increased Nr losses as NO_3^- and N_2, as well as N_2O and NO_x and NH_3. Further experimental data are required to quantify these trade-offs, including at multiseasonal and landscape scales.

427. Clover is an important constituent of many grasslands across Europe, but the quantity of N provided by pasture is highly uncertain. During the growing season, N fixed by legumes will be mostly utilized by the crop (legume or companion crop). However, when active growth slows or ceases, then fixed N may be released to the soil through mineralization, with potential N losses through leaching and denitrification, in particular if the grassland is ploughed or chemically killed (or both) as part of a rotation system. While inclusion of legumes lowers the requirement for applied N (as fertilizer or manure) and the N losses associated with such applications, leaching losses may be greater in fallow periods following legumes if cover crops (see chapter V) are not included in the rotation. Use of intercropping offers the opportunity to make available slow-release N resources from a legume to an intercropped non-leguminous crop, which may reduce N losses.

Table VI.3: Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Landscape Measure 3

Nitrogen form	*NH_3*	*N_2O*	*NO_x*	*NO_3^-*	*N_2*	*Overall N Loss*
UNECE Category	2	2(3)	3(3)	2(3)	3(3)	2(3)
Magnitude of Effect	~↓	↓(↑)[a]	↓(↑)?[a]	↓(↑)[a]	~?	↓(?)[a]

[a] The arrows distinguish a general expected reduction in nitrogen losses compared with use of mineral fertilizers, while acknowledging that post-harvest N losses associated with incorporation of a legume crop into the soil to increase soil C and N stocks can also increase N emissions and leaching losses (shown in brackets).

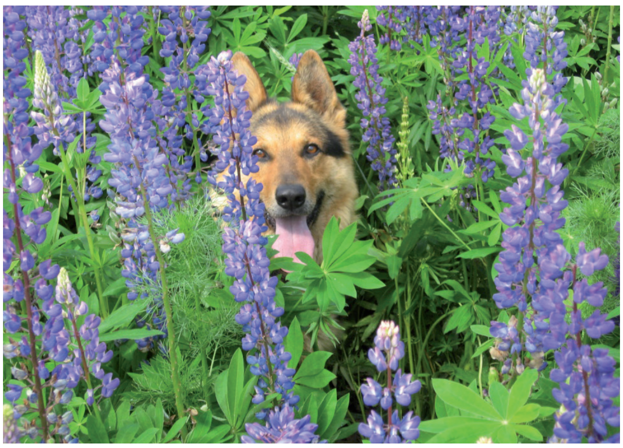


Image 27: Lupine (*Lupinus perennis*) is a nitrogen fixing cover crop that provides a slow-release nitrogen supply through biological fixation (Landscape Measure 3). The shade and evapotranspiration help cool from the summer heat, as also welcomed by Rex, the co-author's dog (photograph: © Sergei Lukin, 2015).

Landscape Measure 4: Introducing agroforestry and trees in the landscape

428. Agroforestry land-uses include the cultivation of crops and trees, with alternate rows of trees and annual crops, or block of trees in the landscape. This approach offers the opportunity for including unfertilized crops in the landscape, such as short-rotation coppices for bioenergy production. This can increase biodiversity, remove surplus N_r from neighbouring arable fields, minimize erosion, provide wind shelter and increase deposition of NH_3 as surface roughness is increased (Sutton and others, 2004; Lawson and others, 2020). All these effects mitigate N_r transport at spatial scales and N_r pollution of air and water (Pavlidis and Tsihrintzis, 2018). The approach may also be compared with Landscape Measures 10 and 12.

Table VI.4: Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Landscape Measure 4

Nitrogen form	NH_3	N_2O	NO_x	NO_3^-	N_2	*Overall N Loss*
UNECE Category	1	3	3	1	3	1
Magnitude of Effect	↓	~↑[a]	~↑[a]	↓↑[a]	~?	↓

[a] The effects will depend on configuration in relation to Nr sources and sinks in a landscape. Agroforestry to increase N sinks between an agricultural area and a stream provide an effective means to mitigate NO_3^- losses. Conversely, recapture of Nr emitted as NH_3 from livestock farms by trees risks increasing soil losses of N_2, NO_x and NO_3^- unless use of fast-growing trees ensures all surplus N_r is taken up by the trees.

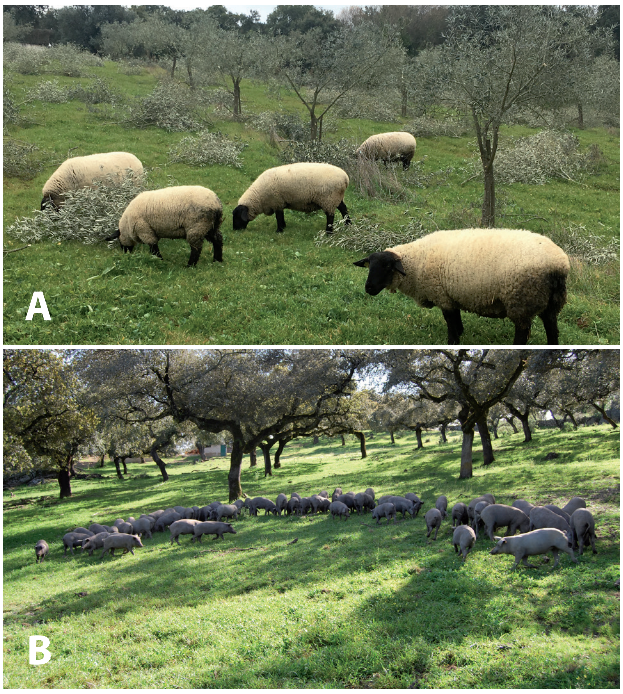


Image 28: A wide range of agroforestry options can contribute to sustainable nitrogen management (Landscape Measure 4). (**A**), Integration of olive trees and extensive sheep grazing (photograph: © António Marques dos Santos, 2019). (**B**), Extensive foraging of Iberian pigs (photograph: © Ministerio Agricultura, Pesca y Alimentación (Spain), 2021).

2. Measures specific to management of riparian areas and waters

429. The main effect of this measure is to reduce the nitrate concentration and adverse effects of N-polluted water that have been lost from agricultural systems, for example, via tile drainage systems, surface fluxes or lateral water fluxes. In-field measures to reduce losses at source are discussed in chapter V.

Landscape Measure 5: Constructed wetlands for stimulating N_r removal

430. Constructed wetlands receive increasing attention due to their wide applicability for removing nutrients from water bodies or for wastewater treatment under various climatic conditions, including from animal manures and wastewater sources (Poach and others, 2003; Muñoz and others, 2016; Caballero-Lajarín and others, 2015; Wu and others, 2016; Vymazal, 2017; De La Mora-Orozco and others, 2018; Luo and others, 2018; Terrero and others, 2020). The design of such constructed wetlands varies considerably, and rates of nutrient removal depend on the plant species used, water-retention times, temperature, type of wetland, etc. (Sutar and others, 2018). The principle of operation of constructed wetlands is to encourage anaerobic conditions that favour denitrification to N_2, while other nutrients accumulate. This means that use of constructed wetlands to remove N_r risks increasing N_2O as well as CH_4 emissions, although further data are needed to quantify the extent of the trade-offs under different management conditions (Garnier and others, 2014). Since the focus is on denitrification, this means that the approach reduces overall landscape-level nitrogen use efficiency, preventing recovery of N_r resources. The popularity of the option is associated with its relative cheapness as a means of managing surface water quality, in comparison with more complex technologies.

Table VI.5: Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Landscape Measure 5

Nitrogen form	NH_3	N_2O	NO_x	NO_3^-	N_2	*Overall N Loss*
UNECE Category [a]	3(3)	3(3)	3(3)	1	3(3)	3(3)
Magnitude of Effect	~?	↑?(↑)	~?	↓↓ (~)	↑(↑↑)	↑(↑↑)

[a] The UNECE category and magnitude of effect are here compared with taking no action – for example, polluted water lost directly to streams and rivers (for example, reference is no action). Values in brackets show consequences compared with a reference system of advanced processes focused on nutrient recovery (chapter IV) (Effects on groundwater are not specified here).

Landscape Measure 6: Planting of paludal cultures in riparian areas or constructed wetlands

431. "Paludal plants" are plants growing in marsh and wetland ecosystems. These plants often develop a significant biomass during the growing period, thereby removing N_r from the water. The biomass can be harvested and used, for example, as a source of bioenergy (Ren and others, 2019). Typical paludal plants used in the context of N_r removal are

Typha latifolia (cat tail), *Arundo plinii* (false reed), *Arundo donax* (perennial cane) or *Phragmites australis* (common reed).

432. Planting of paludal cultures in riparian areas has been shown to be effective in reducing NO_3^- loading in streams, though the efficiency of NO_3^- removal will depend on interactions between riparian hydrological flow paths, soil biogeochemical processes and plant N_r uptake (for example, Hill, 2019). If these wetlands are poorly managed, it is highly likely that the mitigation of NO_3^- will lead to increased emissions of the GHGs N_2O, N_2, CO_2 and CH_4. Further quantitative data on the trade-offs associated with different forms of constructed wetland are needed. It must be recognized that a focus on denitrification in constructed wetlands increases N_2 losses, meaning that the N_r resource is lost, reducing landscape-level nitrogen use efficiency. The advantage of such constructed wetlands is that they are low-cost, while the risks are that the effects on other N_r emissions are generally not quantified. Ensuring effective and rapid growth of paludal cultures will help reduce N_r losses but may be limited in dormant periods (for example, winter season, dry summer season).

Table VI.6: Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Landscape Measure 6

Nitrogen form	*NH_3*	*N_2O*	*NO_x*	*NO_3^-*	*N_2*	*Overall N Loss*
UNECE Category [a]	3(3)	1(3)	2(3)	1(3)	1(3)	2(3)
Magnitude of Effect	~(~?)	↓(↑)	↓(↑)	↓(↑)	↓(↑)	↓(↑)

[a] UNECE category and magnitude of effect are here compared with a constructed wetland that does not include managed growth of paludal cultures, for example, the reference system. Values in brackets show consequences, compared with a reference system of advanced processes focused on nutrient recovery (chapter IV).

Landscape Measure 7: Use of organic layers to promote nitrate removal

433. Denitrification can be promoted, with the objective of reducing nitrates in water, by increasing the organic carbon content in soils, sediments, etc. On a practical level, this is done by introducing so-called "denitrification barriers" into the landscape (Bednarek and others, 2014). The term may appear confusing, but it is widely used to describe physical barriers that promote denitrification. According to Bednarek and others (2014), denitrification barriers can be classified as:

(a) Denitrification walls – constructed from carbon-rich materials, arranged vertically in shallow groundwater, perpendicular to the flow of these waters;

(b) Denitrification beds – containers filled with a material rich in carbon; or as

(c) Denitrification layers – horizontal layers of material rich in carbon.

434. Denitrification is the process by which NO_3^- is converted to N_2. It is a heterotrophic microbial process that uses nitrate as an alternative electron acceptor instead of oxygen in oxygen-limited conditions to oxidize organic matter. In many environmental situations, the rate-limiting step for denitrification is the availability of organic matter. Therefore, the introduction of a carbon-rich layer can be used to promote denitrification.

435. Use of organic layers to promote denitrification can be used for both vertical and lateral water flows. Field and laboratory studies indicate that woodchip bioreactors can achieve nitrate removal efficiencies in a range of 80–100 per cent, with removal efficiencies depending on type and size of the wood chips, hydraulic loading rate, and recovery period between water applications, which affects the hydrolysis rate of the lignocellulose substrate becoming available for denitrification (Lopez-Ponnada and others, 2017). However,

Image 29: Example of a constructed wetland for water treatment by nutrient removal using a paludal culture (common reed, *Phragmites australis*) (Landscape Measure 6) (photograph: © Angel Faz, 2021).

such organic layers may also promote the production of N_2O by denitrification. As anaerobic conditions prevail, significant production of CH_4 may also result, which could create landscape hot spots of GHG emissions (Davis and others, 2019). As the method focuses on promoting denitrification, it reduces landscape-level nitrogen use efficiency, reducing the potential for N_r recovery.

Table VI.7: Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Landscape Measure 7

Nitrogen form	*NH_3*	*N_2O*	*NO_x*	*NO_3^-*	*N_2*	*Overall N Loss*
UNECE Category [a]	3	3	3	1	3	3
Magnitude of Effect	~	↑	↑	↓↓	↑↑	↑↑

[a] The effects are compared with a reference where no technology is used and water moves directly to streams.

Landscape Measure 8: Drainage management

436. Drainage measures, such as insertion of tile drains (promoting run-off and avoiding waterlogging), and water table management, influence the oxygen status of soils (increasing oxygen availability), increasing lateral water transport and reducing residence times of nutrients. All these factors affect the efficiency of N_r removal; for example, via denitrification (see Landscape Measures 5–7). The net consequence is that increasing drainage (such as through the use of tile drains) is expected to help abate emissions of Nr compounds relating to denitrification (N_2O, N_2). In contrast, shorter residence times are likely to increase run-off of NO_3^- into stream waters. This measure can therefore only be considered as suitable where N_2O and N_2 abatement is considered a higher priority than nitrate pollution.

Table VI.8: Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Landscape Measure 8

Nitrogen form	*NH_3*	*N_2O*	*NO_x*	*NO_3^-*	*N_2*	*Overall N Loss*
UNECE Category	3	1	3	3	2	3
Magnitude of Effect	~	↓[a]	↓	↑[a]	↓	~?

[a] Reverse if drains are blocked!

Landscape Measure 9: Stimulating N_r removal in coastal waters

437. Streams and groundwater loaded with N_r might directly reach the sea, specifically in agricultural regions close to coasts. It has been proposed that eel grass, seaweed growing, oyster farming or shellfish aquaculture are suitable for removing excess nutrients from coastal waters (Clements and Comeau, 2019; Kellogg and others, 2014) because nitrogen contained in phytoplankton is incorporated into biomass that is finally harvested, for example, as oysters, mussels or shellfish. However, reports on effects on N_r removal have been found to vary by orders of magnitude across sites, seasons and growing conditions (Kellogg and others, 2014). While the principle of encouraging N_r recovery into useful products is sound, further evidence of the quantitative performance of this system is needed before increased confidence can be given to support its wider adoption to mitigate coastal water pollution.

Table VI.9: Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Landscape Measure 9

Nitrogen form	*NH_3*	*N_2O*	*NO_x*	*NO_3^-*	*N_2*	*Overall N Loss*
UNECE Category	3	3	3	2	2	2
Magnitude of Effect	~	~	~	↓	↓	↓?

3. Afforestation, set-aside and hedgerows as N_r mitigation measures

438. Taking some parts of agricultural land out of production is an effective way to reduce all forms of direct N pollution from agriculture. In this approach, farmland may be converted to other types of land-uses that immobilize N_r and hence reduce N_r cascading at landscape scales. This has large local effects, and can be used for landscape planning, but will also have adverse indirect effects on the agricultural production in the target region. To maintain production, this might require the relocation of intensive agriculture production to other regions or other efficiency improvement measures. This mitigation approach applies, in particular, to low-productivity land, where the opportunities for N_r and other landscape benefits easily outweigh the benefits of keeping the land in agricultural production.

Landscape Measure 10: Introducing trees for afforestation and hedgerows in the landscape

439. Afforestation and the planting of hedgerows or strips of trees around agricultural fields can reduce NO_3^- leaching, and has very positive effects on biodiversity, for example, with regard to pollinators, or soil organic C stocks (Montoya and others, 2020; Thomas and Abbott, 2018; Holden and others, 2019; Ford and others, 2019). Preservation of existing woodland and hedgerow features will help avoid potential negative effects. However, the efficacy of hedgerows for Nr retention will depend on: the size and placement of the hedgerows; the amount of NO_3^- in soil and groundwater; hydrological flow-paths and timing; and landscape biogeochemical conditions in top- and subsoils (Benhamou and others, 2013; Viaud and others, 2005). There is a risk that increased N_r retention might go along with increased soil emissions of N_2O, although the net GHG balance is expected generally to favour reduced net emissions due to the increase in soil C stocks and perennial plant biomass (cf. Butterbach-Bahl and others, 2011). Hedgerows and forest edges also act as biofilters for nearby sources of NH_3 emissions (Kovář and others, 1996. See also Landscape Measure 12).

Table VI.10: Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Landscape Measure 10

Nitrogen form	*NH_3*	*N_2O*	*NO_x*	*NO_3^-*	*N_2*	*Overall N Loss*
UNECE Category	1	3	3	1	3	1
Magnitude of Effect	↓[a]	↓↑[a]	↓↑[a]	↓↓	↑	↓↓

[a] The effects will depend on configuration in relation to Nr sources and sinks in a landscape. Increasing N sinks between an agricultural area and a stream provides an effective means to mitigate NO_3^- losses. Substantial tree plantings are required to mitigate NH_3 emissions, unless close to point sources (Landscape Measure 12). Recapture of N_r emitted as NH_3 risks increasing soil losses of N_2, NO_x and NO_3^-, unless surplus N_r is used in plant growth.

Image 30: Planting a steep-sided valley with trees (Landscape Measure 10) will simultaneously reduce nitrate run-off from surrounding agricultural land, reduce erosion and flooding, and capture atmospheric ammonia, while providing a haven for wildlife (photograph: © Archive of State Institution "Soil Protection Institute of Ukraine", 2013).

Landscape measure 11: Set-aside and other unfertilized grassland

440. Unfertilized grasslands (for example, "set-aside" grassland), have the potential to remove NO_3^- from lateral soil hydrological water flows and can be used as buffers to protect adjacent natural land or streams. The biomass could be harvested for fodder. Unfertilized grasslands also tend to have increased biodiversity compared to fertilized grasslands. If arable land is converted to non-fertilized grasslands, soil C stocks will increase. The measure is mainly targeted at reducing nitrate leaching when set-aside land is placed adjacent to watercourses. The effectiveness of the measure depends on whether overall N inputs are accordingly reduced in the landscape. With appropriate design, there is also potential to reduce denitrification emissions to N_2, but further assessment is needed to demonstrate this.

Table VI.11: Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Landscape Measure 11

Nitrogen form	*NH_3*	*N_2O*	*NO_x*	*NO_3^-*	*N_2*	*Overall N Loss*
UNECE Category [a]	3	2	2	1	2-3	1
Magnitude of Effect [a]	~	~↓	~↓	↓↓	↓	↓↓

[a] The effectiveness of the measure is listed here on the assumption that adoption of set-aside implies a proportionate reduction of N inputs to the agricultural landscape. If N inputs are increased to maintain the same levels of agricultural production, then pollution trade-offs may occur (cf. Landscape Measure 10).

4. Mitigating N_r cascading from livestock hot spots

441. Livestock facilities, including housing, manure storage, or feeding and resting places of livestock kept outside are hot spots of environmental N_r pollution due to ammonia volatilization, N_2O emissions and NO_3^- leaching. This pattern can be exploited to mitigate the often very high point source losses from livestock facilities. Approaches include: the use of shelterbelts around large point sources; and smart relocation of livestock facilities and outdoor animals in a landscape; for example, away from sensitive natural areas such as natural conservation areas, streams, etc.

Landscape Measure 12: Shelterbelts around large point sources

442. Shelterbelts, such as woodland strips or set-aside land, can help to mitigate landscape N_r dispersion from emission hot spots, such as manure storage areas or animal housing facilities. This relies on the function of trees and hedges as biofilters for NH_3, while also promoting dispersion, which reduces local concentrations (Theobald and others, 2001; Bealey and others, 2014). The approach also favours immobilization of N_r into plant biomass and soil organic N stocks (Valkama and others, 2019). Shelterbelts have been shown to significantly promote air NH_3 dispersion and recapture, while at the same time increasing soil C and N stocks, biodiversity etc. (Haddaway and others, 2018). Thus, shelterbelts can also reduce NO_3^- leaching losses due to plant N_r uptake, and/or immobilization in soil organic N stocks. However, N_r immobilization of NH_3 and NO_3^- may increase soil N_2O emissions, although, given the observed increases in soil organic C stocks, the net GHG balance is likely to remain positive. This measure differs from Landscape Measure 10 in its function and effect. The focus here is on actions adjacent to point sources, where biodiversity may be adversely affected due to recapture of high ambient levels of N_r, which must be considered as part of the costs of this measure.

443. In the case of ammonia mitigation using trees, studies have shown that the architecture, placement and area of trees is critical to the success of the measure (for example,

Dragosits and others, 2006; Bealey and others, 2014). For example, a substantial body of trees is needed to allow significant recapture, as contrasted with simply an increase in dispersion. Studies have shown increased N_2O and NO_x emissions from woodland soils in the vicinity of high NH_3 emissions from poultry farming, pointing to a trade-off (Skiba and others, 2006). Appropriate design of tree planting (for example, fast-growth species with high N uptake) may maximize the net benefits and minimize the trade-offs.

444. Given the trade-offs associated with use of shelterbelts and other woodlands as buffers to increase landscape resilience to the effects of nitrogen, it is important to recognize that the approach is not suitable in all contexts. For example:

(a) It is unlikely to be considered appropriate to use a woodland that is prioritized for nature conservation of oligotrophic plant species as a buffer for nitrogen pollution (for example, a site designated under the European Union Habitats Directive), since this would be expected to result in adverse effects on the protected habitat itself;

(b) It is more likely to be considered appropriate to plant a woodland on former agricultural land with the specific purpose of increasing buffering capacity and landscape resilience. Such a planted structure can be designed to help protect priority- designated natural habitats.

Table VI.12: Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Landscape Measure 12

Nitrogen form	NH_3	N_2O	NO_x	NO_3^-	N_2	*Overall N Loss*
UNECE Category	1	3	3	2	3	3
Magnitude of Effect	↓	↑[a]	↑[a]	↓↑[a]	~?	↓↑?

[a] The effects will depend on configuration in relation to N_r sources and sinks in a landscape. Recapture of N_r emitted as NH_3 from livestock farms by trees risks increasing soil losses of N_2, NO_x and NO_3^-, unless use of fast-growing trees ensures all surplus N_r is taken up by the trees.

Landscape Measure 13: Environmentally smart placement of livestock facilities and outdoor animals

445. Livestock facilities, feeding and resting places of outdoor animals can be important point sources of NH_3 and NO_3^-. Thus, such facilities should, as far as possible, be placed far from sensitive terrestrial habitats or water bodies (Panagopoulos and others, 2013). This can significantly reduce local N_r problems, but might require the relocation or even the closure of existing facilities. The approach is most commonly used as part of planning procedures for new developments for proposals to expand existing farms. In particular, where legal requirements apply to protect natural areas (such as the Natura 2000 sites in the European Union), avoiding intensive farm developments in the near vicinity may be one of the smartest approaches to avoid adverse effects on priority habitats. Simple online tools, such as the Simple Calculation of Atmospheric Impact Limits model[34], can be used to support local decision-making (Theobald and others, 2009).

Table VI.13: Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Landscape Measure 13

Nitrogen form	NH_3	N_2O	NO_x	NO_3^-	N_2	*Overall N Loss*
UNECE Category	1	3	3	1	3	1
Magnitude of Effect	↓	~	~	↓	~	↓

5. Smart landscape farming

446. There is often a large potential to optimize the use of the natural resources at the landscape scale. This would deliver a better use efficiency of the nitrogen input (with a resulting general reduction in various types of losses), and a (geographically targeted) lower loss of N to the environment, especially where it has the highest vulnerability to particular types of N compounds.

Landscape Measure 14: Digital planning of land-use on basis of a suitability assessment

447. Land-use and farm planning based on digital 3D precision maps of soil N_r retention can help to optimize fertilizer use and reduce N leaching and other losses. For example, clay and carbon-rich soils have a higher N_r retention capacity than sandy and carbon-poor soils, which may be used to inform fertilizer application rates.

448. In the same way, digital 2D precision maps of subsurface N_r retention can also inform the optimization of fertilizer use, minimizing the impact on groundwater and/or surface waters (Højbjerg and others, 2015). In addition, the reduction of NH_3 emissions from field operations (for example, slurry spreading) can be spatially and temporally targeted, thus increasing N_r use efficiency through space and time. Optimization of land-use and land management (for example, placement of cropping areas and crop rotations in a landscape, introduction of shelterbelts or wetlands, etc.) can help to reduce N_r cascading. In this way, it helps to improve nutrient retention at landscape scale, improve water quality in surface and groundwaters and reduce gaseous N_r losses. However, land-use optimization does require an understanding of landscape fluxes. It typically needs to be supported through detailed modelling, which depends on a sound understanding of soils, groundwater and surface water flows, gaseous transfers through the soil/plant/atmosphere continuum, subsurface geological and geochemical characterization, and consideration of economic constraints (Nguyen and others, 2019; Todman and others, 2019).

34 See www.scail.ceh.ac.uk/.

Table VI.14: Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Landscape Measure 14

Nitrogen form	*NH_3*	*N_2O*	*NO_x*	*NO_3^-*	*N_2*	*Overall N Loss*
UNECE Category	2	2	2	2	2-3[a]	2
Magnitude of Effect	↓	↓	↓	↓↓	↓	↓↓

[a] Further evidence is needed to demonstrate performance.

Landscape Measure 15: Towards mixed farming

449. Mixed farming combines livestock and cropping at farm and landscape scales. It provides opportunities to connect nitrogen inputs and surpluses, with the aim of reducing overall levels of nitrogen pollution and of increasing landscape-scale nitrogen use efficiency. The opposite can be illustrated by the situation where arable farming areas export grain to livestock farming areas, leading to excess manure in the livestock areas that cannot be used locally. Combining cropping and livestock locally can therefore help reduce pollution (for example, Key Action 10 in Sutton and others, 2013; Wilkins and others, 2008).

450. Significant synergies can be expected if mixed farming opportunities are combined with landscape planning (Landscape Measure 14). The goal is to achieve an optimized distribution of manure and fodder import/production between fields and farms (Asai and others, 2018; Garrett and others, 2017). The planning and development of different types of farming will depend on special regional production opportunities or environmental targets for the local area. For example, crop production associated with high environmental N_r losses could be relocated and replaced by extensive low-input farming, if fields are close to nature protection zones. The reconnection of crop and livestock increases the overall landscape-level nitrogen use efficiency and has been demonstrated to reduce N surplus and water pollution (Garnier and others, 2016).

451. Mixed cropping-livestock systems also provide the opportunity to develop free-range livestock production in combination with crops that mitigate N_r losses (for example, trees, Landscape Measure 12). Conversely, there can also be a role for closed high-tech livestock housing systems, where input and outputs to the landscape compartments can be controlled. Since housed livestock systems are associated with much larger NH_3 emissions, the appropriate technical options to reduce emissions from housing, storage and manure utilization need to be incorporated, including consideration of options for N_r recovery (chapters IV and V).

Table VI.15: Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Landscape Measure 14

Nitrogen form	*NH_3*	*N_2O*	*NO_x*	*NO_3^-*	*N_2*	*Overall N Loss*
UNECE Category	2	2	2-3[a]	2	2-3[a]	2
Magnitude of Effect	↓↓	↓↓	↓↓?	↓↓	↓↓?	↓↓

[a] Further evidence is needed to demonstrate performance.

Landscape Measure 16: Landscape-level targeting of technical options to reduce N_r losses

452. In chapters IV and V of the present guidance document, a wide range of technical options have been outlined, including the use of slow-release fertilizers, urea or nitrification inhibitors, acidification of manure, and manure injection in soils. Such measures are also useful at landscape levels, where they are targeted to be used in specific sensitive areas. For instance, more ambitious requirements (for example, requirements for very low-emission animal housing, manure storage and spreading) might be set in the immediate vicinity of wildlife areas, such as local nature reserves or internationally designated sites under the Convention on Wetlands of International Importance especially as Waterfowl Habitat. Planning the use of technical measures within a landscape context requires an understanding of the different

Image 31: Combination of nitrogen emission reduction techniques in a sensitive area (Landscape Measure 16). Here, covered manure storage (Manure Measure 1) is combined with use of a trailing-hose slurry spreader (Field Measure 6) (photograph © L`Albeitar, 2021).

ecological priorities and their local, national and international legislative context. For example, in the European Union, a higher degree of legal protection is accorded to Special Areas of Conservation under the European Union Habitats Directive (requiring a precautionary approach), than may be required for a locally designated reserve (for example, where a balance of economic and environmental objectives may apply).

453. Analysis at the landscape scale can also allow for a more nuanced analysis of the potential trade-offs and synergies between emissions abatement and effects mitigation of different N compounds. For example, manure injection in soils or acidification of slurry can significantly reduce NH_3 volatilization, thus leaving more nitrogen in the soil, which can increase the risk of NO_3^- leaching and N_2O, NO_x and N_2 emissions. Conversely, use of these measures may similarly increase plant nitrogen uptake efficiency, enabling a corresponding reduction of fresh N_r inputs from fertilizers and biological nitrogen fixation. In this way, nitrogen use efficiency may be increased and N_r losses decreased when considered at the level of the landscape as a whole. Landscape application of technical measures allows these interactions to be considered (Theobald and others, 2004); for example, reducing NH_3 emissions will lead to less N deposition to forest and other nature areas (Dragosits and others, 2006), which, in turn, can be expected to reduce indirect NO_x and N_2O emissions from these ecosystems (Cellier and others, 2011).

Table VI.16: Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Landscape Measure 16

Nitrogen form	*NH_3*	*N_2O*	*NO_x*	*NO_3^-*	*N_2*	*Overall N Loss*
UNECE Category	2	2	3	2	3	2
Magnitude of Effect	↓↓	↓	↓?[a]	↓↓	↓?[a]	↓

[a] Less evidence is available for the benefits on NO_x and N_2, though corresponding effects to N_2O can be expected.

Table VI.17: Summary of land-use and landscape management measures and impacts on nitrogen losses

Practice	**Effect**						**Principle**
	NH_3	*N_2O*	*NO_x*	*NO_3^-*	*N_2*	*Overall*	
Measures specific to crops and crop rotations:							
Landscape Measure 1: Increasing land cover with perennial crops	3	2	3	1	3	1	Permanent vegetation cover, highly productive, rapid immobilization of applied N_r in soil organic matter and plant biomass.
	~	↓↑	?	↓↓	↓↑	↓	
Landscape Measure 2: Use of cover crops in arable rotations (use of "catch crops")	3	2	2	1	2	1	Fertilizer and manure applications should be adjusted to account for the N retained. N_2O and NO_x emissions may increase if cover crop is incorporated into the soil.
	~	↓↑	↓↑	↓	↓~↑	↓	
Landscape Measure 3: Inclusion of N_2-fixing plants in crop rotations (including intercropping)	2	2(3)	3(3)	2(3)	3 (3)	2(3)	Reduce mineral N_r use, organic N mineralization better in-line with plant N demand (Values in brackets reflect the effect of increasing soil N stocks).
	~↓	↓(↑)	↓(↑)?	↓(↑)	~?	↓ (?)	
Landscape Measure 4: Introducing agroforestry	1	3	3	1	3	1	Combination of annual and perennial crops, non-competitive exploration of rooting zone, increased N removal per area.
	↓	~↑	~↑	↓↑	~?	↓	
Measures specific to management of riparian areas and waters:							
Landscape Measure 5: Constructed wetlands for stimulating N_r removal	3(3)	3(3)	3(3)	1	3(3)	3(3)	Stimulation of N_r removal via denitrification (Values in brackets compare with a reference system of advanced water processing with nutrient recovery).
	~?	↑?(↑)	~?	↓↓(~)	↑(↑↑)	↓(↑↑)	
Landscape Measure 6: Planting of paludal cultures in riparian areas or constructed wetlands	3(3)	1(3)	2(3)	1(3)	1(3)	2(3)	N_r- fixation in biomass, which can be harvested (Values in brackets compare with a reference system of advanced nutrient processing and recovery).
	~(~?)	↓(↑)	↓(↑)	↓(↑)	↓(↑)	↓(↑)	
Landscape Measure 7: Use of organic layers to promote nitrate removal	3	3	3	1	3	3	Deliberate increase of denitrification reduces nitrate loss to water courses (but wastes N_r resources)
	~	↑	↑	↓↓	↑↑	↑↑	

Practice	Effect						Principle
	NH_3	N_2O	NO_x	NO_3^-	N_2	Overall	
Landscape Measure 8: Drainage management	3	1	3	3	2	3	Aeration of soils, which hampers denitrification but facilitates N leaching (*Reverse if drains are blocked!).
	~	↓*	↓	↑*	↓	~?	
Landscape Measure 9: Stimulating N_r removal in coastal water	3	3	3	2	2	2	Activities to recover N_r in harvests; for example, planting of eelgrass, growing of seaweed, cultivating and harvesting mussels.
	~	~	~	↓	↓	↓?	
Afforestation, set-aside and hedgerows as Nr mitigation measures:							
Landscape Measure 10: Introducing trees for afforestation and hedgerows in the landscape	1	3	3	1	3	1	Selected cutting, continuous forestry / tree management. Planting on steep slopes.
	↓	↓↑	↓↑	↓↓	↑	↓↓	
Landscape Measure 11: Set-aside and other unfertilized grasslands	3	2	2	1	2-3	1	Taking land out of production, might include biomass harvesting.
	~	~↓	~↓	↓↓	↓	↓↓	
Mitigating N_r cascading from livestock hot spots:							
Landscape Measure 12: Shelterbelts around large point sources	1	3	3	2	3	3	Captures ammonia. Disperses the remainder upwards (useful if an N sensitive ecosystem is nearby). Immobilizes N_r in plant biomass.
	↓	↑	↑	↓↑	~?	↓↑?	
Landscape Measure 13: Environmental smart placement of livestock facilities and outdoor animals	1	3	3	1	3	1	Locating livestock facilities away from N_r sensitive ecosystems reduces impact.
	↓	~	~	↓	~	↓	
Smart landscape farming:							
Landscape Measure 14: Digital planning of land-use on basis of a suitability assessment	2	2	2	2	2-3	2	Fertilization loads depen-d on soil properties, parent material, crops, etc.; Placement of crops depends on landscape properties.
	↓	↓	↓	↓↓	↓	↓↓	
Landscape Measure 15: Towards mixed farming	2	2	2-3	2	2-3	2	Helps move to circular agronomy. Improved distribution of manures and fodder production.
	↓↓	↓↓	↓↓?	↓↓	↓↓?	↓↓	
Landscape Measure 16: Landscape-level targeting of technical options to reduce N_r losses	2	2	3	2	3	2	Uses highly effective but high-cost techniques close to sensitive ecosystems.
	↓↓	↓	↓?	↓↓	↓?	↓	

Note: The summary contained in the table above includes the assessed magnitude of effect for the specific submeasures listed: up↑ down↓ or little/no effect indicated by ~, and with double arrows for the largest effects. UNECE categories 1, 2, 3 are estimated. Unless specified, the reference is represented by "no action".

454. In summary, the reviewed land-use and landscape management measures are effective in reducing the overall N_r pollution, and can help increase the effects of the measures reviewed in chapters IV and V, by targeting these measures in space and/or time. Landscape measures can be very effective in mitigating local effects of NO_3^- and NH_3. However, other types of N_r losses and N_r pollution outside of the landscape, must be closely evaluated when implementing end-of-pipe solutions to reach local reduction targets.

H. Priorities for farmers and other practitioners

455. The top land-use and landscape management measures to be implemented in practice can be divided into two groups: those related to a geographically targeted land-use change; and those related to geographically adapted management practices.

456. Some of the top land-use change measures identified during the workshops organized by the European Commission Directorate-General for Environment and the Task Force on Reactive Nitrogen under the Convention on Long-range Transboundary Air Pollution in 2016 and 2019 included:

(a) Set-aside/grassland (with no addition of fertilizers);

(b) Establishment of riparian buffer strips, or biodiversity buffer strips around or within fields (the difference being the proximity to aquatic environment):

(i) Hedgerows and afforestation;

(ii) Changed crop rotation/perennial crops (for example, permanent grasslands);

(iii) Agroforestry;

(iv) Wetlands and watercourse restoration and/or constructed mini-wetlands.

457. In comparison, the suggested management options included geographically targeted implementation of measures such as:

(a) Soil tillage and conservation (for example, no tillage of organic soils);

(b) Drainage measures and controlled drainage;

(c) Grassland management;

(d) Placement of livestock production;

(e) Spatial (re)distribution of manure;

(f) Fertigation and installation of proper irrigation system for dry cultivated areas;

(g) Placement of biogas plants and biorefineries for biomass redistribution.

458. The increased number of farmers turning to practices commonly termed "regenerative agriculture" is recognized, with certain practices having the potential to reduce some N losses, including no-till, organic farming (avoiding manufactured inorganic fertilizers and focusing on biological nitrogen fixation) and activities designed to increase carbon sequestration, etc. Such methods require further assessment to quantify their performance for all forms of N loss.

459. National guidance may be available to consider the effects of such measures. In table VI.18, values from Eriksen and others (2014) are listed for some of the exemplified measures, including budget-economic versus welfare-economic costs (for example, the economic impacts for farming versus the wider economic impact for society). For farmers and other practitioners, the economic costs, and resulting possibilities for compensation for these costs, or payment for ecosystem services provided, will most often be the most important factor for the decision of whether or not to implement the proposed measures. This emphasises the importance of economic cost assessments such as those exemplified in table VI.18, both in relation to the production costs for farmers, and the wider welfare-economic costs relevant to policymakers. Further action is needed on how to monitor the success of measures at a landscape level.

460. In accordance with the general guiding principles, a recommendation for the implementation of efficient land-use and landscape management practices amongst farmers and other practitioners involves the same steps as for the policymakers (see table VI.17). It is recommended that, in addition to assessing the economic costs, each farm should calculate the environmental benefits at farm or landscape level. Such "green accounts" should itemize estimated effects of the measures implemented and report key data about the measures implemented and their efficacy. These data could be collected in a central database, to provide impact assessments for whole landscapes, watersheds, etc., and their specific targets for N reductions.

461. For example, according to the regulations in some UNECE countries, specific N leaching reduction targets are set for each watershed, based on model results or real measurements. In one system, operating in Denmark, farmers within a watershed can voluntarily choose to take actions (for example, whether to plant cover crops), and get financial incentives to meet targets set for the whole watershed each specific year. The alternative is that the farmers will have an obligatory commitment to plant cover crops, until the overall target is met. A geographically targeted and more cost-efficient regulation is thereby implemented.

I. Summary of conclusions and recommendations

462. Overall recommendations are summarized in box VI.2. These recommendations are in line with earlier studies, such as the European Nitrogen Assessment chapter on N flows and fate in rural landscapes (Cellier and others, 2011), and include the following key points and needs for development of new approaches:

(a) The mitigation of N pollution at landscape scale requires consideration of interactions between natural and anthropogenic processes, including farm and other land management;

(b) The complex nature and spatial extent of rural landscapes means that experimental assessment of reactive N flows at this scale is difficult and often incomplete, but should include measurement of N flows in the different compartments of the environment, as well as comprehensive data sets on the environment (soils, hydrology, land-use, etc.) and on farm management.

463. Modelling is the preferred tool for investigating the complex relationships between anthropogenic and natural processes at landscape scale. Verification by measurements is also required, and simple measurements such as NO_3^- concentrations in streams should be considered. It must be recognized that there is a significant time lag between implementation of a control measure and response in stream-water NO_3^- concentrations. However, to date, only the NitroScape model – which was first developed for virtual landscapes (Duretz and others, 2011, under the NitroEurope integrated project) and only recently

Table VI.18: Summary of land-use and landscape management measures and impacts on nitrogen losses

Measure	Comment	Annual N-effect (kg N/ha)	Budget-economic cost (EUR/kg N)	Welfare-economic cost (EUR/kg N)
Set-aside	On rotational land	50	4–25	5–34
Riparian Buffer Strips	From rotation to permanent grass	37–74	6–12	8–16
Afforestation	On rotational land	50	7–20	9–27
Mini-wetlands	Surface run-off	5–20	3–23	4–31

Note: Examples on generalized effects in the form of reduction in N-leaching from the root zone and the related budget- and welfare-economic costs (for example, the economic impacts for farming versus the wider economic impact for society) according to Eriksen and others (2014). Other N effects in relation to nature and climate, and side effects from phosphorus, pesticides are also listed by these authors, but not shown here.

Box VI.2: **Summarizing principles and recommendations for land-use and landscape management N mitigation based on multi-actor discussion.**

Landscape scale N budgeting, which accounts for the main N_r flows, integrates all N_r sources and sinks over space and time, therefore providing the foundations to mobilize a more integrated N assessment to target appropriate measures.

A spatially targeted N budget approach is needed to better manage the N_r resource and operate within N_r limits for a defined area.

N_r budgeting is especially relevant in cases of stable conditions over time (for example, when farming systems are not under transition), and in relation to annual N accounts. In addition, shorter-term and longer-term assessments of N dynamics are important.

Landscape topography and soil properties are important factors controlling the fate of N_r at landscape scales, and the integration of 3D soil and geology maps is important in understanding N_r flows and mitigation options, in particular in relation to N leaching.

Landscape assessment includes evaluation of both sources and sinks, for example, both hot spots for emission and input/reception of N_r in the ecosystems, including effects in sensitive areas and water bodies and effects of atmospheric N_r pollution on terrestrial habitats.

A certain amount of N_r release does not have the same effect at all places in the landscape. This means that landscape measures offer the opportunity to optimize the effects of landscape properties and heterogeneity in relation to N flows and impacts.

The processes for N loss consist of non-linear interactions, are threshold-dependent and are interlinked with acute stressors. Treating these stressors in isolation or in a simplified additive manner may cause pollution swapping and thereby underestimate future N-related risks, including eutrophication, acidification and changes in forests and other terrestrial ecosystems, as well as water systems functions and diversity.

A combination of several N_r mitigation measures is needed to reach multiple sustainable development objectives present in whole landscapes. These need to be ranked in order of importance, as the mitigation of some N flow pathways is more important than others, according to context.

Both the local and global effects of direct N emissions within the landscape, and indirect N emissions induced inside and outside of the landscape, should be included when assessing the impacts of the N mitigation measures.

Landscape-scale measures provide the opportunity for increased retention and sequestration of N in space and time, and thereby the opportunity for increased N harvest and nutrient recovery, optimizing manure redistribution and reducing impact on the aquatic environment, while promoting the bioeconomy.

The operational unit and the related economic benefits and/or trade-offs are important for the effective implementation of landscape scale measures, and vary from farm to farm and from the farm to the landscape scale and beyond (for example, watershed, local and regional scales). Legal frameworks may support optimal implementation. The application of new tools tailored to landscapes is needed to assist the implementation of landscape-scale measures. These can also support strengthening of cultural and natural infrastructures for a more sustainable nitrogen use.

applied to real landscapes (for example, Franqueville and others, 2018, under the French Escapade project) – has integrated all the components of landscape scale N flows: farm functioning; short-range atmospheric transfer; and hydrology and ecosystem modelling. Consequently, the further development and testing of such models is highly recommended, together with their integration into new landscape assessment and decision-support tools.

464. In conclusion, both from an environmental and a socioeconomic perspective, it is important to include landscape management and land-use measures in the mitigation of N pollution. The present chapter recommends a two-step guidance procedure for the implementation of N mitigation measures, and lists selected top measures relevant for policymakers, farmers and other practitioners.

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