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Policy Brief

Baltic Sea Centre
Stockholm University

Effective reduction of nitrogen loads requires targeted measures

Stricter national regulations on fertilisation and improved use of manure in agriculture, as well as set-aside schemes, do have measurable effects on the riverine loads of nitrogen to the Baltic Sea, although it can take up to a decade to reach full depletion of legacies in agricultural soils. However, reaching the environmental goals in a cost-effective way, requires more targeted measures to areas where the risk for leaching is high.

To tackle the eutrophication of the Baltic Sea, total inputs of nitrogen, as well as of phosphorus, need to be significantly reduced. Achieving the goals that the bordering countries and the EU have agreed on through HELCOM's Baltic Sea Action Plan, requires a further reduction of nitrogen inputs to the Baltic Sea as a whole by 11 percent, and to the Baltic Proper by 24 percent.

Almost half of the total nitrogen load (including atmospheric deposition), and just over two thirds of the riverine load, is contributed by diffuse inputs mainly from agricultural land. At the same time, the EU Farm-to-Fork strategy and the UN Colombo declaration set goals, supported by a broad scientific consensus, of halving the nitrogen losses from agriculture in the decade leading to 2030 to bring the nitrogen cycle within sustainable planetary boundaries. Therefore, actions to reduce diffuse nitrogen loads from agriculture are essential but the planning of coordinated measures to reach the targets remains to be done at the scale of the Baltic Sea.

A recent modelling study of Danish watersheds shows that the combined, nation-wide measures of limiting fertilisation rates, improving manure use and mandatory catch crops, did lead to significantly reduced nitrogen losses to the aquatic environment, as did the measure of setting aside some of the arable land. However, legacy effects, largely caused by nitrogen bound in soil organic matter, led to delays until these measures reached their full effect. This makes it crucial to have a long-term approach when implementing measures and a realistic view on when results can be expected. This example also indicates that the required reductions of losses are difficult to reach solely through general regulations.

RECOMMENDATIONS

- Harmonise, facilitate and require nutrient accounting at the field level. Support soil nutrient mapping and precision-agriculture.
- Subsidise cost-effective, targeted measures (e.g. catch-crops, buffer zones and wetlands) based on high-resolution risk maps for nutrient losses established by reference scientific institutions.
- Incentivise agro-ecological and circular practices, in particular the local co-dimensioning of livestock herds and manure quantities, with the crop demand and soil nutrient status.
- Invest in infrastructure and equipment, and promote knowledge transfer for best practices to improve the nutrient utilisation from manure and prevent atmospheric losses.
- Evaluate the effect of policies over the long-term to allow for legacy effects to subside.

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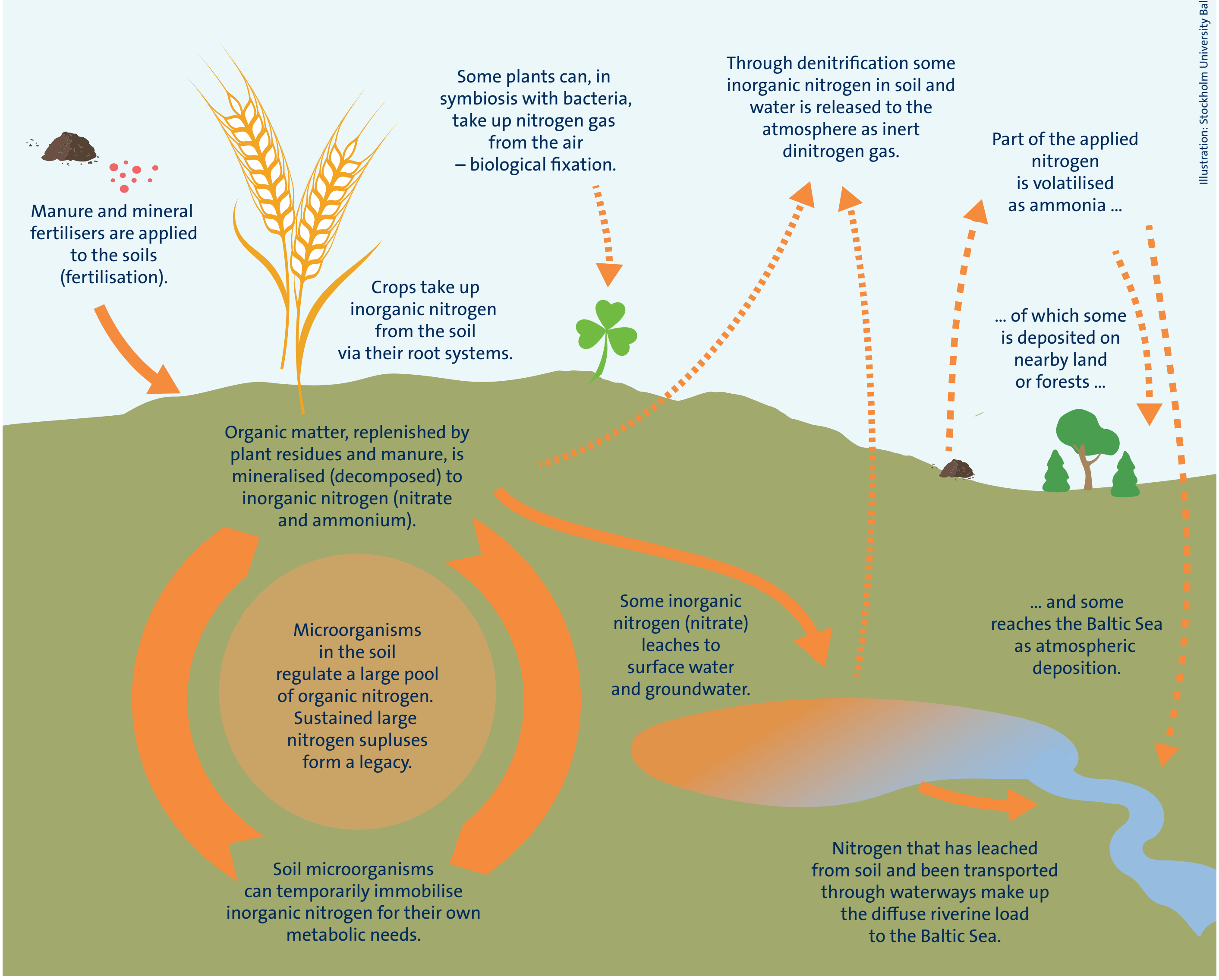
Nitrogen dynamics in arable land



Nitrogen in the agricultural landscape

Nitrogen is abundant in the atmosphere as dinitrogen gas, but this form is not bio-available (useful for plant growth). Only select organisms have the ability to perform nitrogen fixation and turn dinitrogen into ammonia, the main entry point of the reactive nitrogen cycle sustaining the biosphere.

Terrestrial nitrogen occurs overwhelmingly as part of soil organic matter, a wide collection of organic molecules from plant and animal residues with varying degrees of degradability. Soil microorganisms regulate the decomposition (*mineralisation*) of soil organic nitrogen into inorganic forms (ammonium and nitrate, usable by plants), forming an interlinked soil carbon and nitrogen turnover that is strongly influenced by local climate and drainage conditions. Nutrient-efficient cultivation synchronises the crop demand for nitrogen during the growing season with the delivery of inorganic nitrogen from soil mineralisation and external inputs of mineral fertilisers or manure.

Part of the reactive nitrogen applied to fields, both as mineral fertilisers and as manure, is lost to the atmosphere already at the time of application (*volatilisation*). Whereas some is re-deposited on arable land, some is transported to neighbouring land areas, to nearby water bodies or to the sea, thus contributing to the inputs of nitrogen to the Baltic Sea defined as atmospheric deposition.

Nitrates, that are highly soluble and mobile in soil, are susceptible to *leaching* with percolating soil water, flowing to groundwater and aquatic ecosystems, some of it eventually reaching the sea as the diffuse riverine load.

Another major metabolic pathway for the excess nitrogen is *denitrification*, which happens primarily under anoxic conditions either in soil, groundwater, wetlands, or river and lake sediments, whereby reactive nitrogen is transformed back mainly into inert dinitrogen gas (a small fraction forms nitrous oxide which is a very powerful green-house gas). Finally, in periods of large nitrogen surpluses, part of it can *accumulate* as organic matter within agricultural soils, or as nitrates in shallow oxic groundwaters, forming legacies with the potential for delayed release.

The relative importance of all four processes – volatilisation, leaching, denitrification and legacy accumulation – (commonly referred to as losses) depends on present and past nitrogen application practices and on the local ecosystems' capacity to assimilate and retain excess nitrogen.

All losses are inefficiencies for the agricultural sector and carry an economic burden. For the marine environment, it is important to minimise both volatilisation and leaching, which cause eutrophication. In a recently published scientific study, the fate of agricultural nitrogen has been estimated for three cropland-dominated watersheds in Denmark. This type of assessment is inherently specific to the regions and time periods being studied, but can be used as analogues to guide policy in similar contexts.

Modelling the development of nitrogen dynamics in Danish watersheds 1920-2020

Denmark has a long tradition of intensive agriculture, and more than three decades of experience with policies tackling nitrogen pollution. Detailed long-term agricultural statistics allowed to estimate the soil surplus of nitrogen over the past 100 years, while leaching data from monitored agricultural mini-catchments and river load measurements enabled to calibrate models describing the fate of nitrogen from field application to the river outlets, in three major cropland-dominated Danish catchments.

Prior to 1950, the agricultural systems in the three regions were relatively similar and characterised by a large local production of hay and feed to sustain livestock, and a circular re-use of nitrogen in manure. Nitrogen losses were mostly compensated by fixation by legumes in the ley periods. This resulted most years in a low surplus of nitrogen in the soil (10-20 kg N/ha cropland/yr).

1950-1985 Intensive fertilisation causes large surplus

During the 1950s, 1960s and 1970s, mineral fertilizers became the main nitrogen input, while hay and green fodder production decreased in favour of grains, e.g. barley. Regional specialisation also appeared then, consolidating either a predominance of stockless arable farming (surplus near 90 kg N/ha cropland/yr), or mixed pig, dairy and arable farming (surplus at 110-140 kg N/ha cropland/yr). The modelling results show that a soil nitrogen legacy was accumulated following the increase of the soil surplus in the 1960s and 1970s, at rates of 20-40 kg N/ha cropland/yr, at least double the amount exported via rivers in the same period.

1990-2015 Measures deplete soil legacies

To address environmental issues caused by nitrogen pollution, several action plans were adopted nationally, the first one in 1985. Some measures aimed at reducing atmospheric losses of reactive nitrogen (mainly from manure management), others at improving the nutrient efficiency of crop production. One of the measures was a set-aside scheme in place between 1993 and 2008 whereby 8-10 percent of the cropland area had to be managed as unfertilized grassland. Another example included restrictions on application of plant-available nitrogen (at times as low as 20 percent under the economic optimum), improved utilisation of nitrogen in manure and mandatory catch-crops, with the strictest combination of those three measures between 2008 and 2015 (30-35 percent dip of the regional nitrogen surplus).

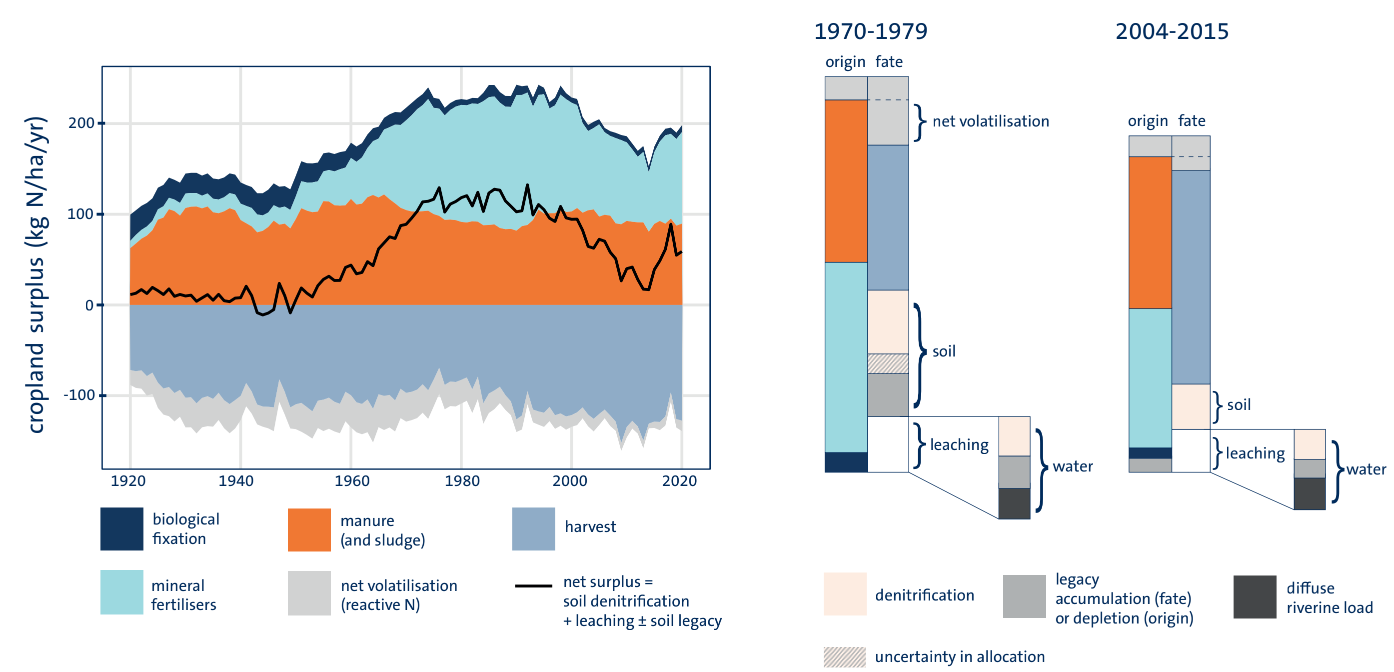
The modelling estimates indicate that the measures in place between 1990 and 2015 depleted the accumulated soil nitrogen legacy, so that all in all, the nitrogen cycle appears to have reverted to a state close to that of 1960. In 2016, a new political agreement lifted the restriction on nitrogen fertilisation which brought the cropland nitrogen surplus back to an intermediate level previously seen in the 1960s.

Changes in denitrification rate and riverine loads

The fate of the nitrogen soil surplus was estimated with the model. Soil denitrification appears as a major nitrogen pathway for the excess or legacy nitrogen, removing 20-60 percent of it from circulation. Cropland appears to always have been a net contributor of nitrate to groundwaters, but looking at the whole watershed, the results indicate a similar pattern of net accumulation of reactive nitrogen in groundwater and the aquatic environment (1960s and 1970s), followed by net depletion (1990-2015). This storage effect was smaller in magnitude than for soils.

The models also allowed to estimate the individual effect of the grass set-asides and the group of measures of 2008-2015 on the diffuse river load, and to extrapolate their full potential. In both cases, it was estimated that the measures showed sizeable effects after 3–4 years and took approximately 8–10 years to show their full effect on the diffuse river load: reductions by 6 percent and 21-27 percent respectively. The delay is mainly explained by the gradual depletion of fresh soil organic nitrogen legacies accumulated in active or set-aside cropland.

Cropland nitrogen budget for the Odense river basin



Dessirier et al 2023 Environ. Res. Lett. 18 104018.

Photo: Johan Bjurer/Mostphotos

Lessons learned from the Danish case

The studied watersheds in Denmark feature simultaneous reductions in cropland fertilisation (18-27 per cent) and in nitrogen losses (53-67 per cent) between the peak of nitrogen legacies and leaching in the 1980s and 2016-2020, via a combination of fertilisation restrictions, improved management of manure, catch crops, and set-asides. However, it takes time to see the results in the riverine nitrogen loads, especially if a period of heavy over-fertilisation has resulted in a build-up of a nitrogen legacy in the soils. Encouraging is that crop production was sustained for grains and even went up for forage in the meantime, meaning that the nutrient-efficiency of crop production improved (note that this study did not model the expected variations in grain quality). It is noteworthy that neither livestock numbers nor the acreage of land in rotation changed significantly since the 1980s in these examples (save for the temporary set-aside scheme), but that instead total fertilisation was mainly adjusted via the amount of mineral fertiliser.

Although it has shown effects, restricting fertilisation below the economic optimum has been a historic exception and is unlikely to provide a politically acceptable solution to fulfil the Farm-to-Fork objective of halving nitrogen losses for systems like Danish agriculture between 2020 and 2030. Instead, the current system in Denmark relies primarily on catch crops on two levels: a universal requirement for all arable land, and targeted catch crops in each coastal river basin set yearly by the government to achieve water quality objectives. The targeted requirements take into account the estimated capacity for denitrification in each catchment and the farmers have the possibility to choose alternative measures based on an equivalency table with targeted catch crops. The scientific focus is to identify zones with a high risk of leaching (low denitrification potential) at a very detailed scale to show where measures can be most cost-effective.

Other countries around the Baltic Sea should take use of the Danish example, and focus the measures against eutrophication in a more targeted way, when the most fundamental regulations against over-fertilisation have been implemented (which is the case in almost all countries). Public subsidies budgeted to support environmental measures should be allocated in accordance with risk maps drawn using tested, scientific methodologies.

Reducing nitrogen losses beyond the reach of targeted measures and further agronomic improvements requires a deeper restructuring of the agri-food system along agroecological principles and dietary guidelines, towards a path with less demand for animal products and livestock, locally reconnected livestock and crop production with lower nutrient intensity and losses.

Nitrogen supply in agriculture

Nitrogen is often the main limiting nutrient in boreal and temperate terrestrial ecosystems due to its relatively high propensity for losses. Natural systems, i.e. non-agricultural, rely on nitrogen-fixing organisms to compensate for these losses.

Agricultural systems have to compensate the nitrogen export incurred by the harvest. Pre-industrial agricultural systems depended largely on fixation in grassland areas for hay production, and on farm animals and their manure to import nitrogen to the fields. This approach set a limit on the nitrogen supply and the yields.

Modern conventional agricultural systems (since ca. 1950) instead rely heavily on industrial mineral nitrogen fertilisers. The introduction of mineral fertilisers did not only boost yields, but has also allowed the decoupling of crop production and animal husbandry. This specialisation of farms and regions created new imbalances, rooted in the disparities between manure production and demand, and led to an era of unprecedented nitrogen soil surpluses. Manure shifted from being a resource to being a by-product spread in excess of crop demand in areas with a high livestock density, while easy access to mineral fertilisers led to over-fertilisation. Altogether, the increasing nitrogen fluxes in agriculture led to elevated river loads of nitrogen and atmospheric emissions/deposition of nitrogen, both of which have contributed to eutrophication of the Baltic Sea.

Agro-ecology advocates a long-term, ecosystem's perspective to farming and to reduce the dependence on externalities such as mineral fertilizers. This often entails locally reconnecting livestock and cropping systems (via feed and manure), accounting for a less intensive production while re-developing the use of nitrogen-fixing crops in the rotations to fulfil the nitrogen demand.

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