acatech POSITION PAPER

Sustainable Nitrogen Use in Agriculture

acatech (Ed.)

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NATIONAL ACADEMY OF SCIENCE AND ENGINEERING

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The acatech POSITION PAPER series

In this series, the Academy publishes position papers on strategic engineering and technology policy issues. The papers contain concrete recommendations and are aimed at decision-makers in government, science and industry, as well as interested members of the general public. The position papers are written by acatech members and other experts and are authorised and published by acatech's Executive Board.

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Executive Summary

What form should agriculture in Germany take in the future? Scientists, policymakers and the general public are currently discussing this question intensively. Sustainable nitrogen use is an important aspect of this discussion, though it has received little public attention so far.

Nitrogen is an essential nutrient for all organisms. In agriculture, it is a component in fertilisers for crop cultivation and in livestock feed. However, crops and livestock do not use all of the nitrogen. In Germany alone, agriculture adds approximately 1.5 million metric tonnes of resource-intensively produced reactive nitrogen to the environment every year. Emissions from agriculture account for around two thirds of all nitrogen emissions in Germany; the remaining third comes from the industrial and energy sectors, transport, and wastewater/surface runoff. Nitrogen in the form of nitrites, nitrates, nitrosamines and as a component of particulate matter poses a risk to human health. Reactive nitrogen in the form of ammonium, ammonia, nitrous oxide, other nitrogen oxides and urea contributes significantly to climate change, biodiversity loss, as well as soil, air and water pollution. As a result, nitrogen inputs from agriculture into the environment are estimated to incur societal costs of between €30 billion and €70 billion a year.

These problems have been known for decades and extensive research has been performed in this area. However, measures implemented to date have not been effective, as indicated by the slow decline of nitrogen inputs from agriculture. This acatech POSITION PAPER takes a systemic look at the nitrogen problem along the entire agricultural value chain, up to and including consumers. The findings are the basis of recommendations for more efficient and sustainable resource utilisation and a reduction of nitrogen inputs into the environment. At most, only a slight drop in agricultural yields can be expected. Therefore, if these recommended activities are implemented, there should be no negative impact on food security in Germany nor a need to increase imports to compensate for lower crop yield. The following measures are proposed for sustainable nitrogen use in the German agricultural sector:

Nitrogen surplus reductions

- The German government's sustainability strategy includes a target of reducing the nitrogen surplus from its current level of over 90 kilograms of nitrogen per hectare of agricultural area to less than 70 kilograms by 2030. However, this target – which was set by policymakers – falls short of what is required. Even if it is met, some 1.2 million metric tonnes of nitrogen will still enter the environment every year, with all the above-mentioned consequences for people and nature. Consequently, the current nitrogen surplus target of 70 kilograms of nitrogen per hectare agricultural area should be reviewed and a lower, evidence-based target established. In some places, lower local targets will be necessary in order to reflect differences in site conditions, especially with regard to soil properties and climatic conditions.

Sustainable agricultural practices

- The concentration of livestock farming must be reduced and crop cultivation and livestock farming again spatially combined to a greater extent. These two measures would significantly diminish regional manure accumulation and are thus key to reducing nitrogen inputs into the environment. They are aimed at regions with high livestock densities and consequently very high nitrogen surpluses, and must be combined with measures to improve animal welfare. As with the nitrogen surplus target, livestock density targets should be determined on a regional basis in accordance with site conditions.
- Conventional and organic farming must go hand in hand and learn from each other. Adapted agricultural practices, especially species-rich crop rotation and demand-based fertilisation, are important for sustainable nitrogen use. Organic farming generally has low nitrogen surpluses and achieves high nitrogen use efficiency, while conventional farming enables high yields with comparatively lower land requirements. A major research and development goal should therefore be to combine the advantages of both systems to close the yield gap and avoid the need to devote more land to food production.

Economic and regulatory framework conditions

- The pricing of nitrogen inputs into the environment is a key instrument to promote both energy and resource efficiency as well as environmental protection. The recent development in mineral fertilizer prices along with sharply rising energy prices and a related decline in the amount of nitrogen used demonstrate the high effectiveness of this control measure. It also allows farms to choose their own individual strategy for reducing their nitrogen surplus. Pricing could be implemented in the form of a nitrogen surplus levy. A tax on mineral fertilisers and off-farm animal feed as a further option for implementing a price system is currently less effective, since it would affect agricultural inputs in general. Moreover, its effectiveness as an incentive to use fertiliser more efficiently has already been forestalled by the prospect of high long-term energy and fertiliser prices. Accordingly, the pricing system design should take the impacts on competitiveness and the effects of major fluctuations in the market price of agricultural inputs into account. Against this background, revenues from pricing should benefit agriculture in the form of a repayment to all farms or as a means of funding further measures to reduce nitrogen surpluses.
- Precise specifications for fertiliser application and on-farm nutrient balancing for almost all farms are key requirements for reducing nitrogen surpluses.
- The German government's current plans should be amended so that more funds are reallocated more quickly from the first pillar of the Common Agricultural Policy (CAP) – which largely comprises area-based direct payments – to the second pillar. This will strengthen the agri-environmental measures in the second pillar, some of which also help to reduce nitrogen inputs into the environment. At the EU level, area-based direct payments should be gradually replaced by payments rewarding environmental and climate protection measures that also aim to reduce nitrogen emissions.
- Measures to reduce the regional concentration of livestock farming must be supported by the relevant building and emission control regulations. Investments that have already been made and grandfather clauses must also be considered. In addition, political measures must ensure that no European or international competitive disadvantages arise. The goal is to prevent more goods with lower production standards from being imported, including from outside the EU.

Knowledge management and sustainable use of technologies

- Efficient fertilizer management using digital technology, low-emission application technologies, precision farming and optimised fertilisers, and by growing varieties bred with specially adapted traits, promotes the sustainable use of fertilizers. A requirement here is the establishment of the necessary basic infrastructure, especially high-speed Internet. Access to finance for the deployment of efficient fertiliser technology and precision farming techniques is also essential.
- Nitrogen-minimised and needs-based precision feeding contribute to reducing nitrogen surpluses and ammonia emissions in livestock farming.
- Comprehensive training and consulting tailored to individual farms can help to change nutrient management practices and should be strengthened through government initiatives and funding.
- More funding needs to be made available for research that involves closer cooperation with farms as partners and demonstration projects, as this type of support advances technology development and promotes the more widespread use of innovative solutions in practice. This research should include key cutting-edge topics in fields such as plant breeding, precision farming and soil microbiome management.

Consumer policy

- Reduced consumption of animal products contributes to decreasing nitrogen emissions and also has benefits for human health, animal welfare and climate protection. Lower consumption can thus be justified on different levels. The task is to promote motive alliances, i.e. different motives and combinations of motives to encourage more sustainable dietary choices and consumer behaviours. Information on reducing the consumption of animal products can be communicated to specific groups.
- One possible approach would be to introduce a tax on animal products, supported by social policy measures, to better reflect the costs to society of livestock farming and the consumption of animal products.

- Behavioural policy instruments have a complementary effect, with the public sector leading the way. For instance, public sector canteens can offer a vegetarian menu as standard to make it easier for consumers to choose sustainably produced products and meals with less meat.
- Food waste along the entire value chain must be avoided or reduced. The less that is wasted, the less fertiliser that is needed to meet demand for food. Food waste can be reduced by informing and educating consumers, organising the distribution of surplus food more effectively and adapting trading standards. As far as possible, the aim should be to create a circular food economy.
- The environmental impacts of producing animal and plant products must be immediately apparent to consumers. For people to make informed purchases and choose sustainably produced products, they need standard, independent and easily understood labelling that informs them about all the key environmental impacts, including those of nitrogen. This also calls for the development of comprehensive database structures containing product and sustainability information that can be easily accessed by the public.

Project

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1 The importance of nitrogen to society

The first plant to use the Haber-Bosch process[1] opened in 1913. This chemical process made it possible to synthesise ammonia from nitrogen and hydrogen[2] on an industrial scale. The advent of synthetic nitrogen fertilisers meant that fertiliser was available in much larger quantities than ever before, helping to pave the way for a revolution in agriculture. Over the next few decades, the industrial scaling of the Haber-Bosch process enabled the production of huge quantities of mineral fertiliser at a cost that kept falling despite its energy-intensive production method. Coupled with the mechanisation and industrialisation of agriculture, the availability of cheap mineral fertilisers enabled a dramatic rise in crop yields. The fact that nitrogen fertilisers are so affordable is hugely important for global food production and food security. The global population rose from 5.3 billion in 1990 to 7.8 billion in 2020.[3] Between 1960 and 2020, the average number of people fed by a single farm in Germany increased eightfold, from 17 to 139.[4] In theory, the food produced in the world today would be sufficient to feed the entire global population if there was no food waste and access to food was not limited, especially by economic factors.[5]

However, there are various drawbacks to the excessive use of nitrogen in agriculture. Excess nitrogen that is not locked into biomass reacts with other elements in the air, water and soil (see panel on the nitrogen cycle in Chapter 3).[6] Excess nitrogen from agricultural applications causes nitrate contamination in groundwater. Another nitrogen compound, nitrous oxide, is a potent greenhouse gas[7] that also contributes to stratospheric ozone depletion.[8] Moreover, nitrogen compounds such as nitrogen oxides and ammonia cause air pollution, especially due to ammonia's role in particulate matter formation. High nitrogen inputs into the environment cause changes in natural habitats that can skew competition between different plant species. Nitrogen inputs can thus result in biodiversity loss in terrestrial habitats and in rivers, lakes and the ocean.

Agriculture is responsible for two thirds of anthropogenic nitrogen inputs into the environment in Germany, while industry, transport and private households are other important sources of reactive nitrogen.[9] We have known for many years that agriculture accounts for a large share of nitrogen inputs into the environment, and the issue has been widely discussed in an environmental policy context.[10, 11] There was a sharp decline in Germany's nitrogen surplus [12] during the early 1990s due to the fall in livestock numbers in eastern Germany. Following a further slight decline, the nitrogen surplus has largely stabilised at a high level over the past decade due to factors such as the rise in biogas production.[13] The average annual nitrogen surplus in Germany between 2015 and 2019 was 92 kilograms of nitrogen per hectare agricultural area.[14] This means that approximately 1.5 million metric tonnes of nitrogen enter the environment every year. Germany has been threatened with heavy fines for repeatedly missing targets established by EU directives over a period of several years (see Chapters 2 and 3). In 2018, the

1 | Named after the chemists Fritz Haber and Carl Bosch.

2 | Climate-neutral hydrogen is key to the decarbonisation of fertiliser production. For background information, see the acatech projects "HySupply – German-Australian Feasibility Study of Hydrogen produced from Renewables" (acatech 2021) and "H_2-Kompass – Wegweiser für Wasserstoff" (acatech 2022), and the Academies' Project Energy Systems of the Future (Leopoldina/acatech/Akademienunion 2022).

3 | See United Nations Department of Economic and Political Affairs 2021.

4 | See BZL 2022.

5 | See WFP 2023.

6 | See Galloway 1998.

7 | See Stocker et al. 2013.

8 | See Kanter et al. 2021.

9 | See UBA 2020a.

10 | See Der Rat von Sachverständigen für Umweltfragen 1985.

11 | See Flaig/Mohr 1996.

12 | The nitrogen surplus per hectare (sometimes referred to as positive nitrogen balance per hectare) is quantified using farm nutrient flow budgets based on the area of agricultural land. The budgets balance the total quantity of nitrogen inputs, e.g. from fertiliser and animal feed, against the total nitrogen uptake by plants and animals. See Chapters 3.3 and 4.2.2., panel on "Calculating fertiliser requirements and nutrient flow accounting".

13 | Since 2005, there has been a particularly strong increase in the cultivation of maize and other energy crops and in the application of nitrogen-rich digestate, see Rösemann et al. 2021.

14 | See BMEL 2022b.

European Court of Justice found Germany to be in breach of the Nitrates Directive and required it to take measures to tackle nitrate contamination in groundwater. However, even since the amended Fertiliser Ordinance (German: Düngeverordnung) came into force in May 2020, little has changed with regard to the key factors for sustainable nitrogen use in agriculture.

In view of the significant percentage of nitrogen inputs caused by agriculture and the pivotal role of farming in food production and in the preservation of the cultural landscape, this acatech POSITION PAPER focuses on the agricultural sector. While a systemic analysis of how to tackle emissions from other sectors is also necessary, it is beyond the current paper's focus on nitrogen emissions from agriculture. Accordingly, this acatech POSITION PAPER concentrates on the problems caused by agricultural nitrogen inputs into the environment and the associated topics. The recommendations for policymakers and the public outline a possible future approach to managing nitrogen in agriculture. Sustainable nitrogen use must reduce the negative environmental impacts of nitrogen while still maintaining food security.

This acatech POSITION PAPER was motivated by the ineffectiveness of the measures taken to date. It looks at the entire agricultural system from the perspective of the three – economic, environmental and social – dimensions of sustainability. It is important to recognise that agriculture forms part of a wider public debate in which other connected themes also feature prominently, for example climate change and greenhouse gas emissions, the use of plant protection products and biodiversity, healthy food and diets, and livestock farming and animal welfare.

Measures geared towards sustainable nitrogen use must aim to effectively reduce nitrogen inputs into the environment while also addressing other environmental protection issues such as biodiversity conservation and animal welfare. Other factors that must be taken into account include economic conditions in the agricultural sector, society's need for food security and consumer demand for agricultural produce (see Chapter 2). While nitrogen is an essential nutrient, excessive nitrogen use can have negative environmental impacts (see Chapter 3). If agriculture is understood as part of a complex system, strategies to reduce nitrogen surpluses and emissions can be targeted at different subsystems and processes in the value chain (see Figure 1). Following an analysis of these strategies in Chapter 4, concrete recommendations are formulated in Chapter 5.

2 Agriculture as part of a complex system

Food goes through numerous production, processing and trading stages before it reaches our plates. The agricultural sector plays a key role and also involves several other actors (see Figure 1). It is thus essential to include these actors to provide a sound basis for the formulation of effective recommendations to reduce nitrogen emissions.

2.1 Changes in the farming industry

There has been a huge increase in agricultural yield per hectare since the beginning of the 20th century. For example, the average yield for wheat climbed from around 1.9 metric tonnes per hectare in 1900 to around 7.7 metric tonnes per hectare between 2010 and 2015 (see Figure 2).[15] As well as the increased use of nitrogen fertilisers, other factors that contributed to this rise include advances in breeding, land improvement measures,[16] chemical plant protection products and improved production methods thanks to the use of efficient machinery and equipment. Farming practices are also increasingly influenced by the ongoing trends of digitalisation and mechanisation, as seen for example in precision farming (see Chapter 4.3.1). These rapid changes in production methods have been accompanied by a transformation in economic, social and political attitudes

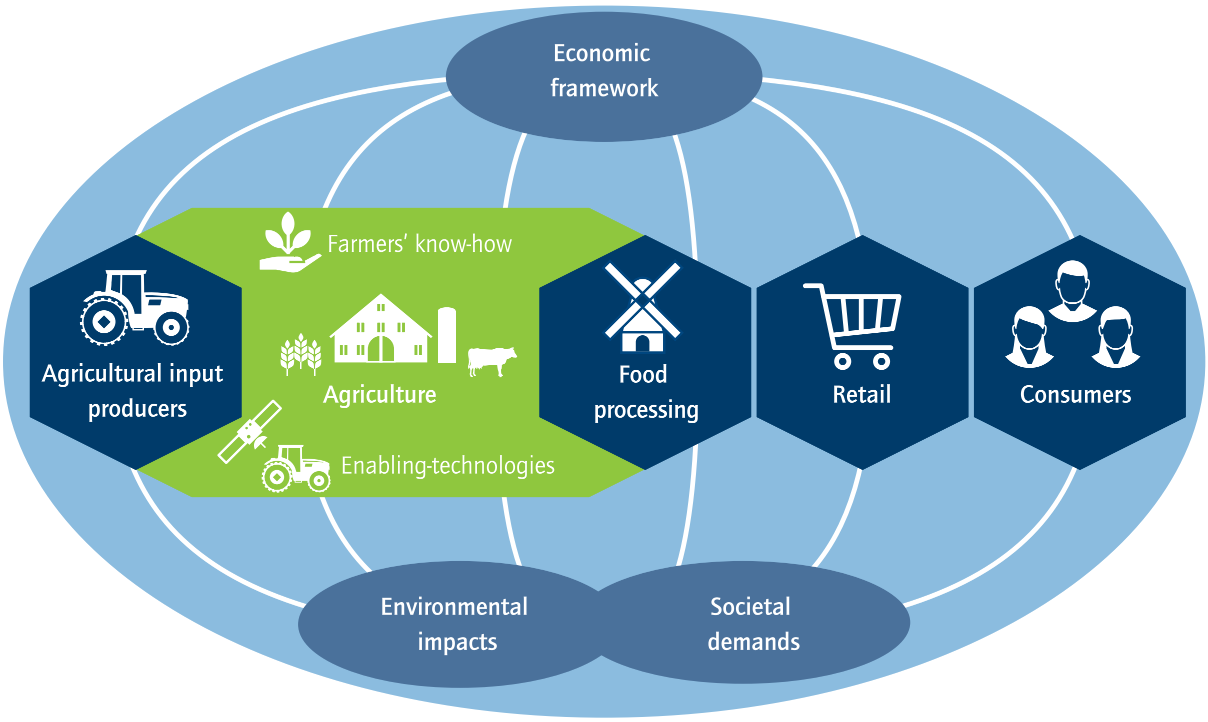

Figure 1: Agricultural sector value chain. The full value chain includes everything from agricultural input producers and food production and trading to the end consumer. Food production has environmental impacts, is embedded in the overall economic framework and must meet society's needs (Source: authors' own illustration).

15 | See Deutscher Bauernverband e.V. 2022.

16 | Land improvement measures are measures to maintain or enhance the soil fertility of agricultural land. They include e.g. irrigation or drainage, construction of flood defences for flood plains and wasteland reclamation.

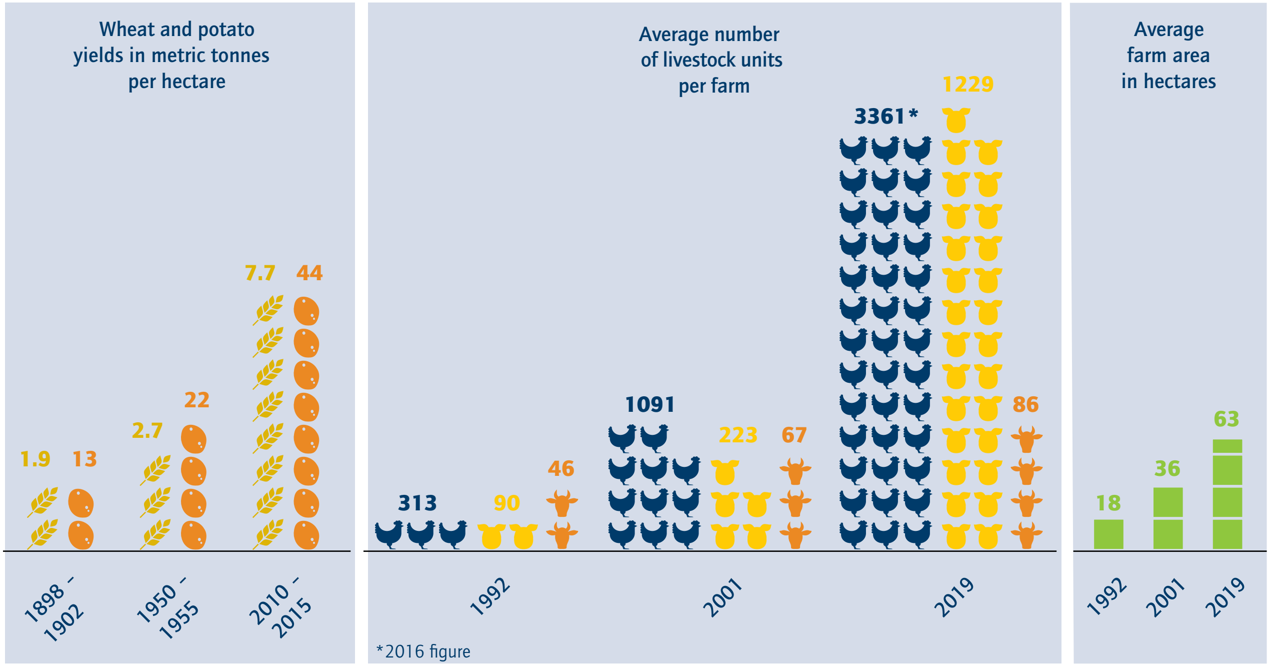

Figure 2: Growth in yields, number of livestock units per farm and farm area. The illustration shows wheat and potato yields in Germany (averaged over five-year periods) since the start of the 20th century (left), the average number of livestock units per farm (centre) and the average cultivated area of arable farms for individual years (right) (Sources: authors' own illustration based on data from – left to right – Deutscher Bauernverband e.V. 2022, BLE 2020a and Destatis 2021).

towards farming, influenced by the fact that it is now a global industry. While on the one hand this leads to the tensions implicit in global competition, global markets are also key to ensuring a secure food supply.[17]

Local differences due to regional variation in soil properties and climatic conditions mean that different types of farming – e.g. grassland, arable farming, vegetable farming and livestock farming – are prevalent in different parts of Germany. The main products of each region influence the regional nitrogen cycle. In recent decades, many farms have become highly specialised, often concentrating on a single type of production. This is particularly evident in the concentration of livestock farms in certain regions (see Figure 7), with significant repercussions for the regional nitrogen budget (see Chapter 3.2). Since overall livestock numbers in Germany are high, the production and importation of protein-rich feed is extremely important – domestic feed production takes up just over half of all agricultural land.

The number of livestock units per farm has grown significantly over time (see Figure 2). It rose from an average of 67 in 2001 to 86 in 2018 on cattle farms, and from 223 to 1,229 on pig farms over the same period. Arable farms have experienced a similar scale of change over the past few decades. There has been a sharp decline in the number of farms, with individual farms now cultivating a much larger area of land. This trend continues to be driven by the greater efficiency of mechanised farming, which allows large areas of land to be worked relatively quickly. At the same time, the use of nitrogenous fertilisers grew during the 20th century, although it has remained stable in recent decades both in Germany[18] and worldwide[19].

Approximately 90% of Germany's agricultural area is farmed conventionally. In 2021, organic farms accounted for 10.8% of all agricultural land in Germany, or about 1.8 million hectares.[20] There is no doubt that organic farming is growing rapidly – the area of organically farmed land has increased by almost 60%

17 | See acatech 2020.
18 | See Statista 2020.
19 | See Brightling 2018.
20 | See BÖLW 2022.

in just five years. In the organic livestock farming sector, there is considerable variation in the market share of different products – only eggs, mutton and goat meat have a share of more than 10% of the total market.[21] Coupled with rising consumer demand for sustainably produced products, the policy goals of increasing organic farming's share of agricultural area to 30% in Germany [22] and 25% in the EU[23] by 2030 mean that organic farming's importance will continue to grow in years to come.[24, 25]

2.2 Agriculture and the environment

Unlike almost any other industry, farming is carried out directly in and with the environment. Since farming practices, including fertilisation, take place in an open system comprising soil, plants, groundwater and the atmosphere, they inevitably affect the environment. The negative environmental impacts of agriculture generate external costs that are not included in the price of agricultural produce. In Germany alone, these costs are estimated to be in the region of €90 billion a year.[26] A significant proportion of these costs is due to environmental damage caused by nitrogen compounds, which were responsible for external costs of €30–70 billion in 2015.[27, 28] The overall external costs associated with agriculture have a number of different causes. Methane emissions from cattle and nitrous oxide emissions from soil and fertiliser contribute to climate change. Farming practices are also a significant factor in the biodiversity loss that has occurred in recent decades, chiefly due to the intensive exploitation of agricultural land and the introduction of plant protection products and fertiliser into the environment (see Chapter 3.1).[29] When transported by wind and water into terrestrial and aquatic habitats, these inputs also have a significant impact on non-agricultural land. Other environmental impacts of using land for farming include reduced soil organism activity, soil erosion and nitrate contamination in groundwater. Costs are associated with all of these impacts – for example, the cost to the European economy of agricultural sector compliance with the relevant air quality standards would be significantly lower than the cost of dealing with the human health and environmental impacts of air pollution.[30, 31] The impacts to which nitrogen compounds are a major contributor are also at the forefront of the public debate regarding sustainable farming.

2.3 Agriculture and policy

Sustainable agriculture has become a prominent topic in the public and policy debate. This was reflected in the Federal Chancellery's appointment of the "Commission on the Future of Agriculture", which published its findings in the summer of 2021. Extensive discussions with members of the commission provided valuable feedback on the problems associated with nitrogen for this acatech POSITION PAPER. Similar discussions were also held with members of the "Animal Husbandry Competence Network" (German: Kompetenznetzwerk Nutztierhaltung), also known as the *Borchert* *Commission.* Both commissions argue that while it is urgently necessary to reduce agriculture's environmental impacts and improve animal welfare, the industry must also be

21 | See Schaack et al. 2017.
22 | See SPD/Bündnis 90/Die Grünen/FDP 2021.
23 | See Europäische Kommission 2020a.
24 | See UBA 2021a.
25 | See acatech 2019.
26 | See Kurth et al. 2019.
27 | See UBA 2021b.
28 | The wide range is due to the fact that a comprehensive estimate of the environmental costs can only be produced using simplified assumptions. For details of the methodology and uncertainties in the estimates, see Brink et al. 2011.
29 | See Leopoldina/acatech/Akademienunion 2020.
30 | See Giannakis et al. 2019.
31 | See Giannadaki et al. 2018.

able to plan for the long term. All the factors relevant to the agricultural sector must therefore be fully taken into account.[32] Furthermore, sustainable farming is moving up the policy agenda in connection with the production of renewable raw materials and bioenergy, which will be increasingly important as fossil fuel substitutes in the context of the bioeconomy and energy transition.

Policy and statutory measures at national and EU level will be essential to reduce nitrogen inputs into the environment. At EU level, agriculture is currently addressed under the Common Agricultural Policy (CAP), primarily through subsidies that include environmental criteria (cross-compliance and greening rules). There are also several stringent European regulations concerning the protection of waterbodies, habitats, species, air quality and the climate that are directly or indirectly relevant to sustainable nitrogen use in agriculture. These regulations are usually transposed into national law in the form of ordinances. Various EU regulations also establish pan-European standards for organic production and product labelling.[33]

Since it was established in 1962, the Common Agricultural Policy (CAP) has mainly focused on providing consumers with sufficient food at affordable prices, increasing productivity and supporting farmers' incomes.[34] The CAP consists of two "pillars". The first pillar involves area-based direct payments to farmers. The EU expanded its agricultural policy in response to growing public debate about the environmental impacts of agricultural production. Cross-compliance and greening rules[35] were added to the first pillar, while support for agri-environmental measures was added to the second pillar, which concerns rural development. This step ensured that the EU's agricultural policy complied with the formal responsibility[36] to integrate environmental protection requirements into the definition and implementation of the Union's policies and activities.

The subsidies paid to farmers in Germany under the first pillar currently amount to approximately €4.85 billion a year, all of which comes from the European Agricultural Guarantee Fund (EAGF).[37] The second pillar provides around €1.3 billion in EU funding that must be co-financed by additional national funding.[38] The member states have a degree of flexibility in how they implement the CAP. For instance, they can transfer some of their CAP allocations from the first to the second pillar, although Germany has hitherto made limited use of this option.[39]

In addition to the Common Agricultural Policy, the EU's member states have also passed several Directives aimed at protecting the environment. The standards contained in these Directives[40] for the protection of waterbodies, groundwater bodies and marine waters, air and atmospheric quality, and wild species and habitats require the member states to meet stringent targets for the ecological conservation status of waterbodies and habitats. Germany has also committed to improving the ecological status of marine waters under the EU's Marine Strategy Framework Directive.[41] Germany has achieved significant improvements in some of the above areas, for example the nitrate concentration in running waters and the total nitrogen concentration in the rivers flowing into the North and Baltic Seas. However, the overall targets have not been met in any of the relevant areas (see Chapter 3.1), even though they have been mandatory for several

32 | Appointed by the Federal Ministry of Food and Agriculture (BMEL) to study ways of achieving sustainable livestock farming, the Borchert Commission has stressed the importance of guaranteeing long-term funding. The Commission has proposed various options for transforming animal husbandry, see Kompetenznetzwerk Nutztierhaltung 2020. These options include different financing models such as increasing V.A.T. on animal products and using the revenue to transform the livestock farming industry. A feasibility study of the legal basis of these options has also been carried out, see Karpenstein et al. 2021. For further details, see Chapters 4.2.1 and 4.4. Also appointed by the Federal Ministry of Food and Agriculture, the Commission on the Future of Agriculture included agricultural stakeholders – from farmers' organisations to NGOs – in order to develop a comprehensive future vision of sustainable agriculture. This vision addresses all the different types of farming and their interactions with society and the environment from the perspective of the three – social, environmental and economic – dimensions of sustainability, see Zukunftskommission Landwirtschaft 2021.

33 | See Regulation (EU) 2018/848 that came into force in 2022, repealing Council Regulation (EC) 834/2007, which applied until 31.12.2021.

34 | See AUEV 2012, Art. 39.

35 | See BMEL 2019b. These include minimum standards for soil protection, water law, environmental protection, animal welfare, and food and feed safety.

36 | See AUEV 2012, Art. 11.

37 | See BLE 2020c

38 | See BMEL 2019b

39 | See Europäische Kommission 2020b.

40 | See e.g. Habitats Directive 1992; Water Framework Directive 2000; Birds Directive 2009.

41 | The reduction of nitrogen inputs is at the heart of efforts to improve the quality of the marine environment among the countries bordering the North Sea (OSPAR Commission) and the Baltic Sea (Helsinki Commission).

decades. Many of the targets and rules in the Directives are directly or indirectly relevant to the input of reactive nitrogen into the environment and thus to the use of nitrogen in agriculture.[42]

The EU Nitrates Directive [43] has received much attention in recent times due to the infringement proceedings and the ruling that Germany has breached the Directive. In 2017, several amendments were made to Germany's fertiliser law as a result of the previously initiated and ongoing proceedings for infringement of the Nitrates Directive and the ruling against Germany. The Bundesrat approved the Federal Ministry of Food and Agriculture's draft of a new General Administrative Regulation for the designation of nitrate-contaminated and eutrophicated areas (German: AVV Gebietsausweisung – AVV GeA) in July 2022. The regulation stipulates that the nitrate monitoring network must be expanded.[44] The relevant rules in Germany's Fertiliser Act (German: Düngegesetz) and Fertiliser Ordinance (German: Düngeverordnung – DüV) have been tightened and the Nitrogen Balance Budget Ordinance (German: Stoffstrombilanzverordnung) enacted. These measures show that Germany is relying primarily on regulatory instruments to ensure compliance with the EU Nitrates Directive and reduce agricultural nitrogen inputs into the environment, since voluntary measures have proven ineffective.

In addition, farms that use fertiliser must comply with federal and state regulations to protect water resources and ecosystems.[45] The provisions of federal emission control law and the Federal Building Code are also relevant to livestock farms. These regulate matters such as the size, location and emissions of livestock housing. However, soil management is only governed by the non-binding rules of good agricultural practice.[46]

2.4 Agriculture, society and consumption

In addition to the prevailing production conditions, economic factors and consumer behaviour are also key to determining the options available for achieving sustainable nitrogen use. Meanwhile, a stable income and the ability to plan for the long term – for example to make investments – are of paramount importance to farmers. This means that the production of sustainable food must be profitable for the farms that produce it and the products in question must have a market. There must be demand for these products and the desire and opportunity to buy them. While on the one hand the retail trade responds to consumer demand patterns and communicates them to producers via marketing companies, it also has a major influence on consumer behaviour, for example through its pricing policy and through product promotion and placement.

In recent years, demand for plant-based alternatives to meat and dairy products has grown strongly in Germany, driven by increased consumer awareness of issues relating to animal welfare, the climate footprint of meat and dairy products, sustainable production, healthy eating and, more generally, new products that have come into the market.[47] At the same time, although per capita consumption of fresh milk products fell between 2000 and 2021, cheese consumption actually rose.[48, 49] Apparent consumption per capita of meat products declined by 12% over the same period, from 91.5 kilograms to 81.7 kilograms.[50] This trend was accompanied by a greater focus on exports, especially of pork and poultry.[51] As a result, after a downturn in the early 2000s, there has been very little further decline in German livestock farming over the last few years. Moreover, while surveys show that 52% of Germans consider a product's

42 | See Möckel/Wolf 2020.
43 | See Nitrates Directive 1991.
44 | See BMEL 2022d.
45 | See e.g. BNatSchG 2009, Art 34; WHG 2020, Art 38a.
46 | See BBodSchG 1998, Art 17.
47 | See BMEL 2021b.
48 | In absolute terms, annual per capita consumption of fresh milk products fell from 93.7 kilograms to 84.2 kilograms over this period. Per capita cheese consumption increased from 21.2 kilograms to 25.3 kilograms. When comparing these figures, it is important to remember that more milk is used to produce one kilogram of cheese than for many fresh milk products.
49 | See BLE 2022.
50 | See BMEL 2022c. Per capita human consumption fell from 61.5 kilograms to 55.0 kilograms over this period. The human consumption figure is estimated on the basis of factors including boned carcass weight, feed and industrial losses. Apparent consumption is calculated as production plus imports minus exports.
51 | See Thünen-Institut 2022.

sustainability when deciding what food to buy, price remains the most important driver of their purchase decisions.[52, 53]

Reducing food waste also indirectly helps to cut nitrogen inputs into the environment. Food loss occurs during harvesting, transport, storage and processing, as well as at the consumption stage. According to the United Nations' Food Waste Index Report 2021, approximately 931 million metric tonnes of food waste was generated worldwide in 2019, 61% of which came from households.[54] The picture is similar in Germany: households are responsible for the majority of food waste (55%), whereas significantly less food is thrown away in the food processing industry (15%), out-of-home eating sector (13%), agricultural sector (11%) and food retail sector (4%).[55]

Public attitudes towards agriculture are also extremely important to its future development. Some people are critical of agriculture, mainly because of its environmental impacts and the use of highly automated production methods. Moreover, many members of the public have very little idea about how farms actually operate.[56, 57] As a result, people often believe that small-scale, rural farms are best,[58] even though these characteristics in fact say very little about the sustainability of agricultural practices and the financial conditions in the agricultural sector.

52 | See Lehmann et al. 2022
53 | See Ernst & Young GmbH 2020.
54 | See United Nations Environment Programme 2021.
55 | See Universität Stuttgart 2019.
56 | See Zander et al. 2013.
57 | See Kantar Emnid 2017.
58 | See Zander et al. 2013.

3 Nitrogen in agriculture and the environment

Nitrogen is an essential nutrient in the metabolism of all living organisms and is key to a continuously productive farming system. Around half of the nitrogen used in Germany's agricultural sector remains in the environment[59] – with serious consequences for humans and the natural world. While much of the public debate is focused on nitrate contamination in groundwater, the significant and direct impacts of reactive nitrogen on biodiversity and as a greenhouse gas often receive less attention. The different nitrogen compounds in water, the soil and the atmosphere are mobile. The nitrogen cycle (see panel below and Figure 3) shows how nitrogen emissions are distributed in the environment.

The nitrogen cycle

Nitrogen is present in the metabolism of all living organisms as a component of nucleic and amino acids, the building blocks of DNA and proteins. This nitrogen is not "consumed" – it is converted into different forms through natural processes and recycled in metabolic cycles. For example, nitrogen present in the soil is taken up by plants, which in turn provide food for animals. The animals excrete part of this plant matter, returning it to the soil so a new cycle can begin.

These cycles only involve "reactive nitrogen", which occurs naturally in the environment or enters it through anthropogenic emissions. Elemental nitrogen (N_2), on the other hand, is not reactive in the atmosphere since it does not easily form compounds with other elements. Reactive nitrogen occurs as different molecules: the gases ammonia (NH_3), nitrous oxide (N_2O) and other nitrogen oxides (NO_x) are found in the atmosphere, while ammonium (NH_4+), nitrite (NO_2–) and nitrate (NO_3–) are found in soil and water. In living organisms, microbial processes convert atmospheric nitrogen into reactive nitrogen in a process known as nitrogen fixation. Reactive nitrogen can also be produced by other natural processes such as lightning and fires.

Anthropogenic inputs of reactive mineral nitrogen generated by the Haber-Bosch process accounted for 73% of reactive nitrogen inputs into the natural environment in Germany in 2012 and 2013, and their volume has not decreased significantly since.[60]Because natural mechanisms are unable to break down all of this reactive nitrogen,[61] it is building up continuously in the environment, with all the consequences that this entails (see Chapter 3.1). Reactive nitrogen is constantly being converted by microorganisms in the soil through oxidation and reduction processes. The most important process in quantitative terms is mineralisation, where reactive nitrogen in organic matter such as animal manure and soil organic matter is converted into ammonium and nitrate. Biological processes also release nitrogen from the soil into the atmosphere in the form of nitrous oxide, nitrogen oxides, elemental nitrogen and in livestock farming mainly as ammonia. As with other emissions, these compounds are transported to other places by wind and water, where they are recorded as deposition in nitrogen budgets.

As soon as reactive nitrogen enters the environment, it disperses into the atmosphere, soil and water and is almost impossible to recover. Its mobility and its impacts in the atmosphere, water and soil and on living organisms are described by the "nitrogen cascade" (see Figure 3).[62]

59 | See Möckel/Wolf 2020.
60 | See UBA 2015.
61 | See Galloway 1998.
62 | See ibid.

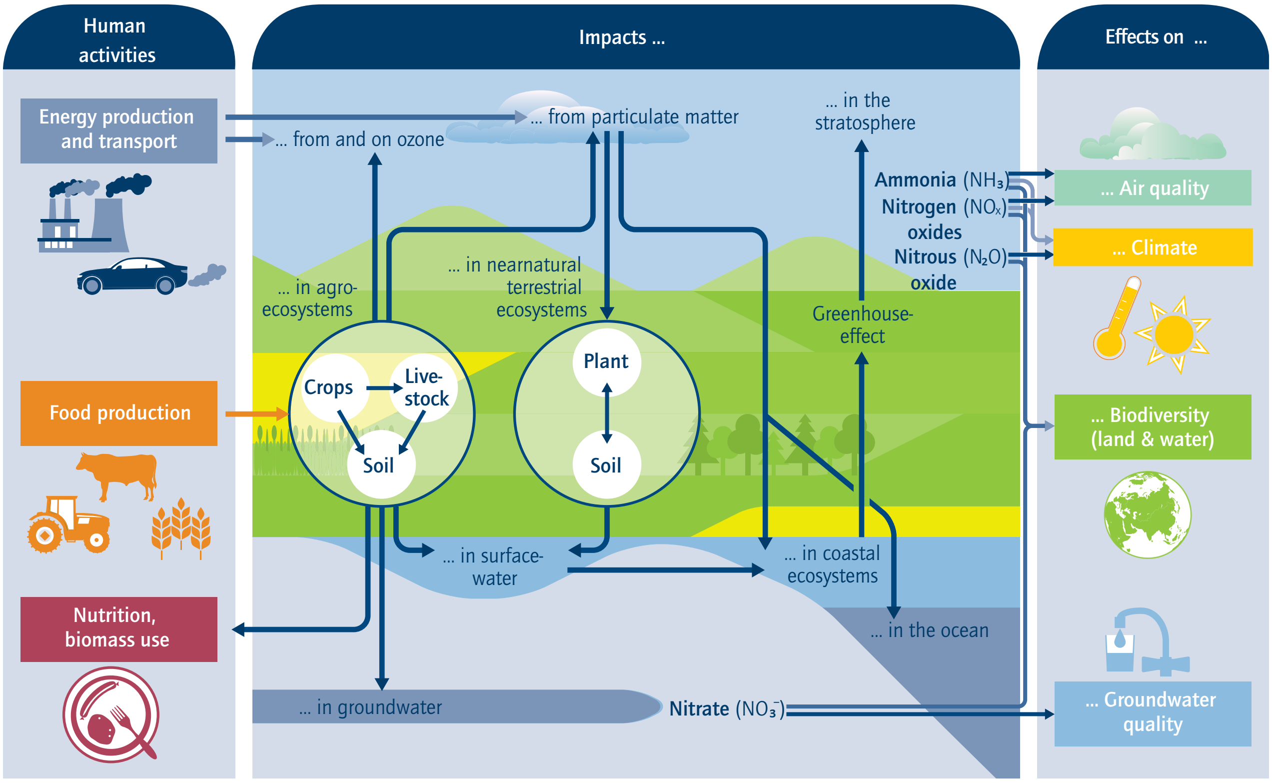

Figure 3: The nitrogen cascade: Reactive nitrogen moves freely between the atmosphere, water and the under-ground environment, where it has multiple impacts on ecosystems (Source: adapted from UBA 2015 and Galloway et al. 2003).

3.1 Nitrogen in the environment

In Germany, agriculture is the main source of nitrogen emissions (63%), followed by the industrial and energy sectors (15%), transport (13%) and wastewater/surface runoff (9%).[63] While ammonia (NH_3) accounts for the largest quantitative share of these emissions, nitrous oxide (N_2O) and nitrogen oxide (NO_x) emissions from agriculture are also significant (see Figure 4). It should be noted that soil gas emissions are not recorded by monitoring networks – emission factors are used to produce an approximation, and the figures are thus inevitably subject to some uncertainty. The emission factors are being constantly updated on the basis of ongoing research into the diverse and complex interactions that occur in the soil. While this can sometimes have a pronounced effect on the calculated emission levels, the order of magnitude of the emissions and the significance of their impacts remains unchanged.[64]

63 | See UBA 2015.

64 | For instance, the emission factor for nitrous oxide in the German emissions inventory was adjusted to reflect regional soil properties in the National Inventory Report 2022. This gives an average emission factor that is lower than the IPCC standard emission factor previously used for all regions. As a result, the estimated N_2O emissions of approximately 22 million metric tonnes CO_2 equivalent are significantly lower than the previous figure of approximately 28 million metric tonnes CO_2 equivalent, see Thünen-Institut 2021; Mathivanan et al. 2021.

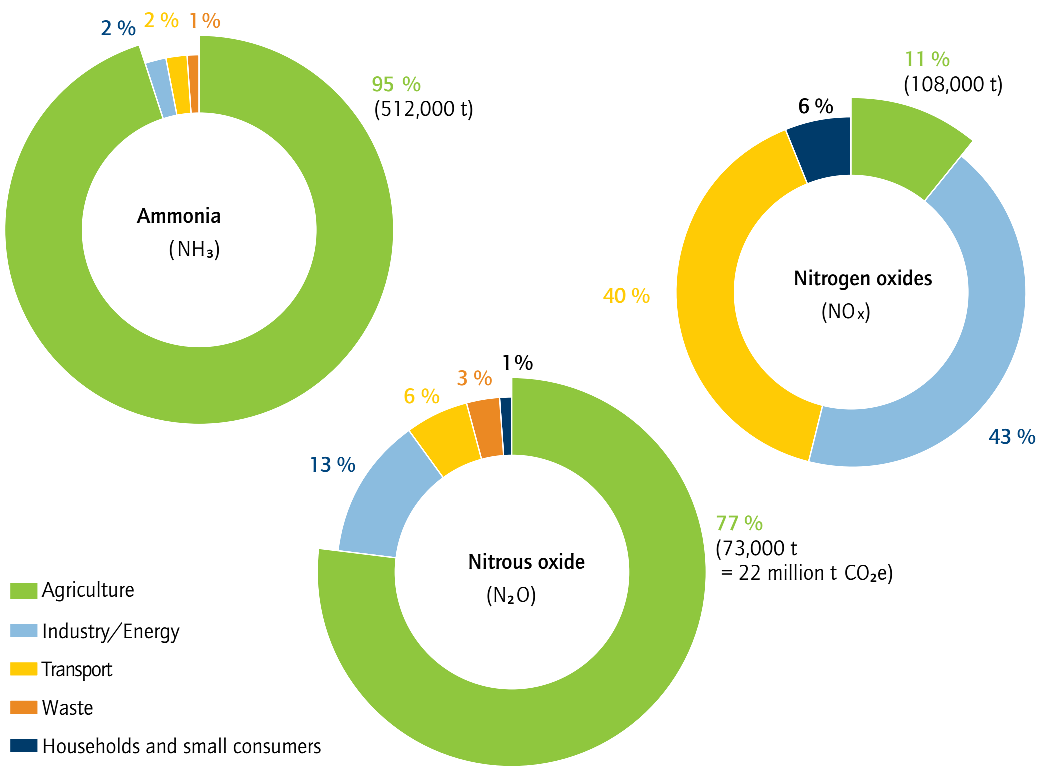

Figure 4: Sources of emissions of different gaseous nitrogen compounds (2018; N2O: 2019) and absolute figures for emissions from agriculture (Source: authors' own illustration based on UBA 2022a and UBA 2022b)

Large quantities of nitrous oxide (N_2O) are produced through microbial conversion of nitrogen-rich mineral and organic fertiliser in the soil[65] (see panel on the nitrogen cycle). Nitrous oxide is responsible for a significant proportion (approximately 22 million metric tonnes CO_2 equivalent) of greenhouse gas emissions from agriculture in Germany.[66] Depending on local environmental conditions, the climate impact of reducing N_2O emissions from agriculture can be up to twice as great as the impact achievable through soil carbon storage.[67] Moreover, nitrous oxide also contributes to stratospheric ozone depletion.[68] Solar UV radiation breaks the N_2O down slowly, allowing the breakdown products to destroy ozone. While chlorofluorocarbon (CFC) emissions have declined in recent decades, there is now significantly more long-lived N_2O in the atmosphere. This has become the main cause of anthropogenic stratospheric ozone depletion and the annual hole in the ozone layer.[69]

In addition to nitrous oxide, other gaseous nitrogen compounds – nitrogen oxides (NO_x) and ammonia (NH_3) – also have negative impacts on air quality.[70] Ammonia can combine with other atmospheric pollutants to promote particulate matter formation.[71, 72] Particulate matter can cause inflammation of the

65 | See Bremner 1997.
66 | See UBA 2022a.
67 | See Lawrence et al. 2021.
68 | See Kanter et al. 2021.
69 | See Ravishankara et al. 2009.
70 | See Behera et al. 2013.
71 | See Renard et al. 2004.
72 | See Wang et al. 2020.

tissue in our airways,[73, 74] potentially leading to chronic respiratory disease in the event of high-level, long-term exposure.[75] As a result of this and other effects e.g. on the cardiovascular system, high exposure to particulate matter is associated with increased mortality.[76] Air pollution in general is one of the leading human health risk factors, alongside high blood pressure, diabetes and smoking.[77]

Like air, soil and drinking water are also shared resources that are essential to our survival. Nitrate (NO_3) leaches from the topsoil into lower soil layers. Depending on soil type and thickness, it can take years or even decades for it to be transported from the Earth's surface into aquifers.[78] This means that changes in nitrate inputs into the soil take a long time to show up.[79] According to the data collected by both the EU nitrate monitoring network and the EU Water Framework Directive monitoring network in Germany, in the last decade around a quarter of the monitoring stations in the EU reporting monitoring station network exceeded the safe level for drinking water of 50 mg of nitrate per litre.[80,81] The EU nitrate monitoring network data sets show that this percentage has hardly declined at all over the past decade, while the nitrogen surplus in the agricultural sector also only decreased slightly during the same period [82] (see Chapter 3.3). Consequently, the fact that it takes a long time for nitrate to be transported through the soil will not be enough in itself to significantly improve the nitrate levels recorded in groundwater if there is only a small change in nitrate inputs into the soil.

There is currently some controversy regarding the representativeness of the networks for monitoring the regional distribution of nitrate contamination within Germany's federal states.[83] It is essential to expand and connect sufficiently representative monitoring networks in order to map small-scale and regional differences. In the case of high nitrate concentrations, it is important to remember that the empirical link between groundwater nitrate concentrations and nitrogen balance surpluses can vary considerably from region to region due to differences in weather and soil conditions (see also Figure 7). However, these uncertainties are not large enough to call the general existence of nitrate pollution or the impact of agriculture's high nitrogen surpluses into question. It should also be stressed that the European Court of Justice ruling was based on an analysis of the regulatory framework in Germany as well as on the nitrate concentration levels recorded by the monitoring network.

Nitrate enters the human body through the consumption of fresh vegetables, drinking water, cereals and fruit, and can indirectly cause a number of health disorders. While nitrate itself is largely harmless, it can be broken down into nitrite in the human body. Nitrite is more reactive than nitrate and can significantly reduce oxygen uptake in the blood, especially in babies under the age of three months. Moreover, nitrosamines produced from nitrite in the gut have been found to be carcinogenic. Long-term intake of high quantities of nitrate is therefore considered to pose a health risk. The World Health Organization (WHO) defines the acceptable daily intake as 3.7 milligrams/kilograms bodyweight. Based on an average bodyweight of 70 kilograms, the mean per capita intake in Germany of 101 mg/day is currently well below this limit.[84] The chain of chemical reactions required to produce carcinogenic nitrosamines from nitrate means that the intake of a certain quantity of nitrate is only indirectly harmful to human health. Consequently, the acceptable daily intake for nitrate and the drinking water limit of 50 mg of nitrate per litre are based on the precautionary principle.

Although nitrate is only indirectly harmful to human health, the direct impacts of nitrate and other nitrogen compounds on ecosystems are major drivers of biodiversity loss and eutrophication in waterbodies. For instance, reactive nitrogen inputs from neighbouring farms are a significant contributor to animal and

73 | See Peden 2001.
74 | See Barraza-Villarreal Albino et al. 2008.
75 | See Park et al. 2021.
76 | See Lelieveld et al. 2015; Pope/Dockery 2006.
77 | See GBD 2019 Risk Factors Collaborators 2020.
78 | See Di/Cameron 2002; Cameron/Haynes 1986.
79 | See BGR 2019.
80 | See BMEL/BMU 2020.
81 | See Deutsche Bundesregierung 2021.
82 | See Häußermann et al. 2019.
83 | For a detailed discussion of the calls for representative networks and the associated challenges, see BMEL/BMU 2020.
84 | See LfL 2021b.

plant species declines, especially in near-natural terrestrial ecosystems.[85] There are multiple adverse effects on biodiversity. Reactive nitrogen inputs into natural ecosystems alter the soil conditions through processes such as soil acidification. The different physiological responses of plants to changes in soil conditions are often associated with negative impacts on plant health.[86] Nitrogen inputs also skew natural competition between plants. In nutrient-poor habitats with plant species adapted to these conditions – for example dry grassland, moorland and peatland – nitrogen inputs allow plants that are better at using nitrogen for growth to colonise the area and dominate the local vegetation, eventually leading to its disappearance.[87] And even in ecosystems like meadows that are not highly nutrient-limited, nitrogen inputs alter the species composition, favouring grasses over herbaceous plants.[88] In total, 68% of all sensitive terrestrial ecosystems were contaminated with excessive nitrogen inputs in 2015,[89] while around half of red-listed plant species are threatened by increased nitrogen inputs.[90] Declines in plant biodiversity also affect microbial and animal biodiversity. Many herbivorous insect species are now endangered, even in nature reserves, because their host plants are becoming increasingly rare due to the effects of atmospheric nitrogen deposition.[91]

Nitrogen inputs also harm water quality in surface waterbodies such as streams, rivers and lakes. Here too, they can cause animal mortality by altering the composition of plant and algal communities.[92] Nitrogen applied to farmland is transported via rivers into the sea where it promotes strong algal growth. Once the algae die, they sink to the bottom of the sea where they are broken down by microbes. The dramatic reduction in water oxygen concentration caused by this process creates dead zones where higher organisms are no longer able to survive.[93] Coastal water quality is also affected. Although nitrogen inputs have declined in recent decades, 55% of North Sea waters and 100% of German Baltic waters are still eutrophic.[94] From 2012 to 2014, an average of between 71% and 78% of nitrogen inputs from Germany into the North and Baltic seas came from agriculture.[95]

3.2 Nitrogen in agriculture

Regardless of whether they use conventional or organic farming methods, farmers would not be able to provide us with a secure food supply without fertiliser. The growth and yield of all crops are highly dependent on the availability of key nutrients such as nitrogen, phosphorus and potassium as well as various micronutrients. To ensure good crop yields, it is thus essential to provide the right nutrient inputs. To do this, farmers use mineral fertilisers, farm manure, digestate, compost and green manure, i.e. nitrogen-fixing plants (legumes or other crops such as mustard) that are grown on farmland and then incorporated into the soil where they deliver their nitrogen content. A substantial proportion of the nitrogen in farm manure, digestate, compost and green manure is chemically bound in organic compounds and only becomes available to plants once these have decomposed in the soil. This necessary mineralisation process (see panel on the nitrogen cycle) means that the nitrogen in farm manure is released over a long period of time.

In 2019, nitrogen inputs from the German agricultural sector mainly comprised mineral fertilisers (48%) and animal feed (36%).[96] All of the mineral fertiliser came from conventional farming, since its use is not permitted on organic farms.[97] Animal feed is not just used to meet livestock's nutritional requirements; the addition of certain nutrients – especially proteins – promotes the animals' growth with a view to achieving continuously high performance and productivity for products such as eggs, meat and milk. The feed must satisfy different requirements in terms of nutritional energy, amino acids and other nutrients, depending on the animal's genetic make-up and physiological condition. On

85 | See Leopoldina/acatech/Akademienunion 2020.
86 | See Bobbink et al. 2010.
87 | See Bobbink et al. 2010.
88 | See Dise et al. 2011.
89 | See Schaap et al. 2018.
90 | See UBA 2015.
91 | See Habel et al. 2016.
92 | See BMU/BfN 2020.
93 | See Diaz/Rosenberg 2008.
94 | See BMU 2018a; BMU 2018b.
95 | See ibid.
96 | See BMEL 2022b.
97 | See Regulation (EU) 2018/848 2022, Art. 9 and Annex II, Section 1.9.8.

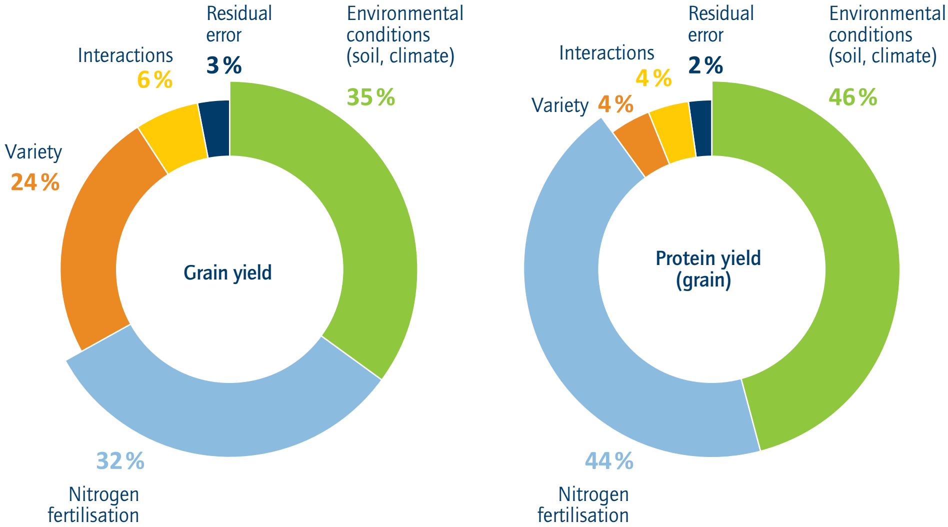

Figure 5: Influence of nitrogen fertilisation and other parameters on wheat grain and protein yield. Together with environmental conditions and crop variety, nitrogen fertilisation is one of the key factors in important agronomical crop traits such as grain and protein yield. The percentages in the illustration are taken from a Swiss study of wheat in which "environmental conditions" refer to local conditions such as cli-mate and soil type. The "interactions" category quantifies interdependencies between individual factors (Source: authors' own illustration based on Häner / Brabant 2016).

the whole, most of the nitrogen in animal feed is currently excreted by livestock and reused as manure, but some is also released into the environment. Only 3%–31% remains bound in animal products,[98, 99] although this figure can be optimised through changes to livestock feeding practices (see Chapter 4.3.1).

In Germany, the main sources of protein for livestock are grain, grass silage, rapeseed meal, maize and soybean. The EU imported a total of 35.7 million metric tonnes of soy products in 2018, much of which was duty-free soy from South America.[100] The clearing of rainforest for soy production has made this a controversial issue. From 2014 to 2019, soy product imports accounted for between one quarter and one third of protein feeds in Germany.[101, 102] Several crop processing by-products from domestic agricultural production are also used, for example bran, draff, stillage, beet pulp and rapeseed meal. Since these by-products are rich in nitrogen and other nutrients, recycling them as livestock feed is a good example of the synergies between crop cultivation and livestock farming and constitutes an important sustainable farming practice.

The example of wheat illustrates the importance of nitrogen availability for grain crop yield and protein content (see Figure 5). Grain protein content is a key quality parameter for wheat, which is one of the main arable products in Germany. Its importance is largely due to the correlation between baking properties and protein content and the fact that food production is more profitable than animal feed production. When wheat is harvested, it is sorted into different quality and price classes based on its grain protein content, ranging from "elite wheat" to "feed wheat". The economic importance of nitrogen fertilisation is thus reinforced by its major influence on yield and protein content.

The exact amount of nitrogen that needs to be added depends first and foremost on on-site conditions. The main factors are

98 | See Smil 2001.
99 | See Shepon et al. 2016.
100 | See European Commission 2017.
101 | See BLE 2020b.
102 | See Verband der ölsaaten-verarbeitenden Industrie in Deutschland 2020.

yield potential (determined by soil condition and natural environmental conditions), choice of crop type and target market (e.g. baking wheat), crop rotation and all other management practices. Of the more commonly grown crops, nitrogen-fixing legumes – i.e. pulses such as peas, broad beans or lupins and clover-like feed plants such as lucerne, red clover and sainfoin – are particularly important for crop rotation, since their symbiotic relationship with soil microorganisms allows them to fix atmospheric nitrogen. The symbiotically fixed nitrogen is either taken up by the crop or initially remains in the soil with the crop and root residues before eventually being released after conversion by soil organisms. This means that the next crop in the crop rotation system requires significantly less nitrogen fertilisation, even though some of the nitrogen can be carried away by wind and water. This nitrogen-saving effect is one of the reasons why the amount of land used for growing legumes rose from 102,500 hectares in 2014 to over 222,000 hectares in 2020.[103] This trend was also driven by Common Agricultural Policy (CAP) greening measures and the growth of organic farming.

Legumes are indispensable in organic farming, which does not use mineral fertilisers. As a result, the overall nitrogen surplus of organic farming is significantly lower than in conventional farming.[104, 105] However, depending on the context, organic farming yields can be anywhere between 3% and 53% lower,[106, 107, 108] meaning that more land may be needed to achieve the same yields as conventional farming.

3.3 The nitrogen surplus from agriculture in Germany

The nitrogen surplus (sometimes referred to as the positive nitrogen balance per hectare) is quantified using farm nitrogen balance accounting based on the area of agricultural land (see the panel on calculating fertiliser requirements and nitrogen balance accounting, Chapter 4.2.2). It is calculated as the sum of total nitrogen inputs, e.g. from fertiliser and feed, minus the nitrogen taken up by plants and animals. In Germany, the total annual surplus is approximately 1.5 million tonnes of reactive nitrogen.[109] For the period 2015–2019, the average annual nitrogen surplus in Germany was 92 kilograms of nitrogen per hectare agricultural area.[110] The spatial distribution of the nitrogen balance sheds light on some of the causes of this surplus. It indicates that areas with a high livestock density have particularly high nitrogen surpluses (see Figure 7).[111] The fact that livestock farming and correspondingly large quantities of farm manure are concentrated in certain regions is one of the main causes of regional nitrogen surpluses.[112]

Although there has been a slight fall in the average nitrogen surplus in Germany in recent decades, this decline has slowed significantly during the last ten years (see Figure 6). The current five-year average is still a long way off the target of 70 kilograms of nitrogen per hectare in the German government's sustainability strategy.[113, 114] If the present trend continues, the target is unlikely to be met through current measures alone, even considering the amendments to the Fertiliser Ordinance (German: Düngeverordnung – DüV) (see Chapter 4.2.2).[115] Moreover, the target of 70 kilograms of nitrogen per hectare – which was set by policymakers – is still rather high and unambitious. The Agriculture Commission at the German Federal Environment Agency,

103 | See BLE 2020b.
104 | See Sanders/Heß 2019.
105 | See Chmelíková et al. 2021.
106 | See Haller et al. 2020.
107 | See WBAE 2016.
108 | See Seufert et al. 2012.
109 | See Taube et al. 2020.
110 | It is estimated that there is an error margin of approximately 8 kilograms of nitrogen per hectare agricultural area due to possible inaccuracies in the numerical data. For a detailed analysis, see Häußermann et al. 2019.
111 | See BMEL 2019c, two livestock units is the equivalent of two full-grown cattle, approximately ten slaughter-weight pigs or 500 poultry.
112 | See Häußermann et al. 2019. The correlation coefficient for the relationship between livestock density and nitrogen surplus is $R^2 = 0.82$.
113 | See Deutsche Bundesregierung 2016.
114 | See UBA 2020b.
115 | See Taube et al. 2020.

for example, is calling for a target of 50 kilograms of nitrogen per hectare on the grounds that this is necessary to meet the relevant soil conservation and air and water quality goals.[116] According to the Commission, this figure aims to strike a compromise between the environmental impacts of nitrogen inputs, the economic effects on yield and profits, and practicability, which takes into account the farm's current situation and its potential to reduce nitrogen.

Even the 50 kilograms of nitrogen per hectare figure can be seen as an interim target, the ultimate aim being to further reduce the nitrogen surplus until an as-yet-undefined "tolerable" level is attained. The scientific definition of this level will be a challenging process that must be carried out in a transparent, evidence-based manner and include all the relevant stakeholders. On the one hand, it must be recognised that it will not be possible to completely prevent nitrogen inputs into the environment in the open system of soil, water and atmosphere. On the other hand, in view of the scientifically proven impacts (see Chapter 3.1), a significant reduction in the reactive nitrogen

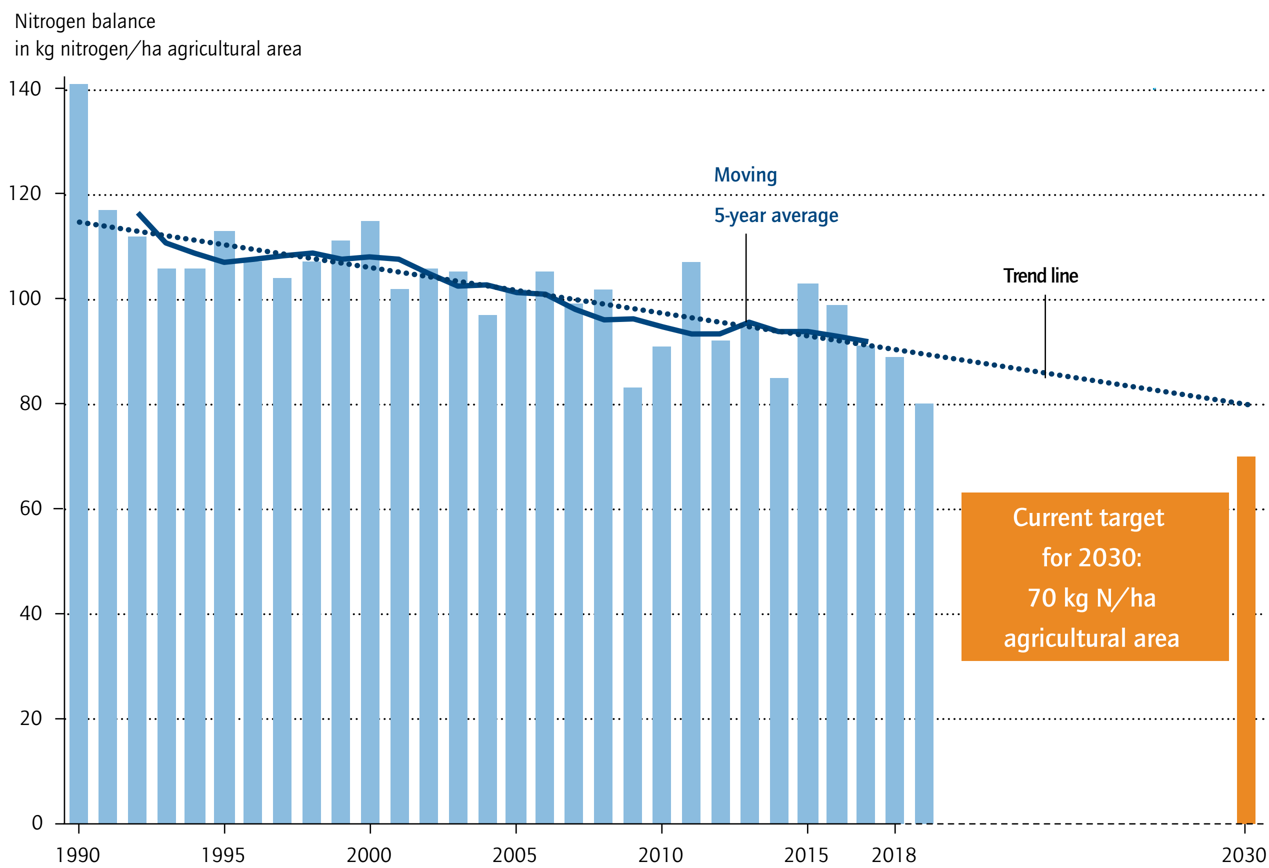

Figure 6: The annual nitrogen balance of the German agricultural sector (total nitrogen balance) and the moving five-year average (solid line). The 2030 target is taken from the German government's sustainability strategy (Source: authors' own illustration based on BMEL 2022a).

116 | See UBA 2015b.

surplus is extremely important, especially from an environmental and climate protection perspective. When weighing up these different aspects, it will also be necessary to take different regional conditions and ecological vulnerabilities into account. Chapters 4 and 5 discuss the priority areas that should be included in an overarching strategy for reducing the nitrogen surplus.

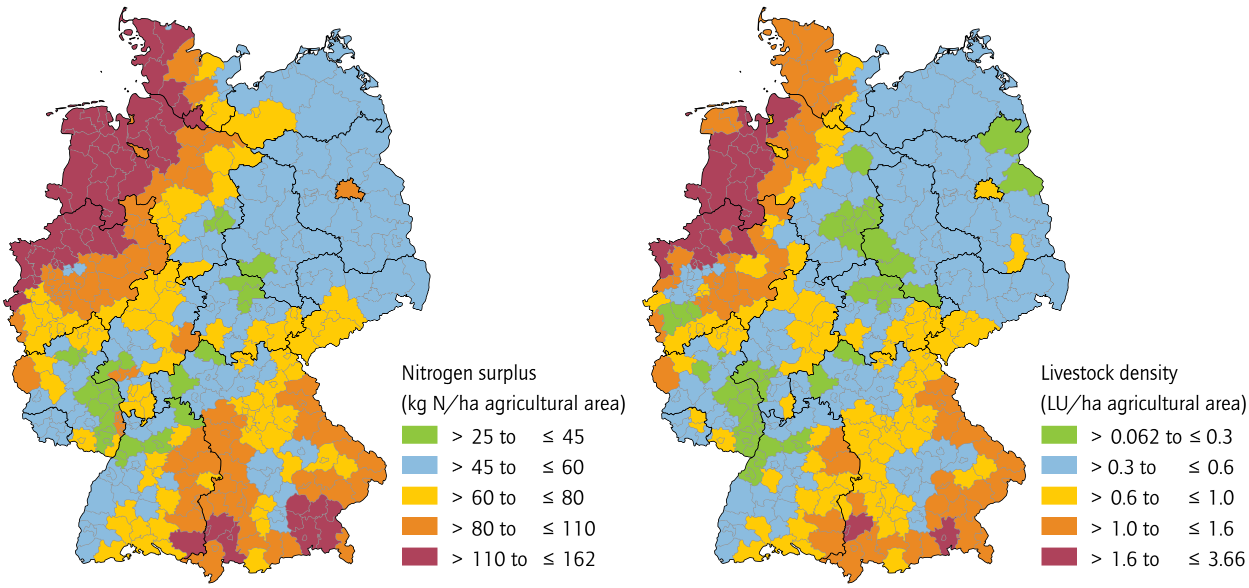

Figure 7: Nitrogen surpluses in the agricultural sector in kg N (left), and livestock density in livestock units (right), both per hectare of agricultural area at district level (mean values for 2015–2017). When interpreting the nitrogen surplus map (left), it is important to bear in mind that although the highest nitrogen surpluses are concentrated in certain regions, even the green-shaded regions still have significant nitrogen sur-pluses. It should also be noted that the number of livestock and area of agricultural land are low in ab-solute terms in urban regions such as Berlin (Source: Häußermann et al. 2019).

4 Analysis of priority areas for promoting sustainable nitrogen use

Measures geared towards sustainable nitrogen use must resolve the conflict between fertilisation requirements and excessive agricultural nitrogen inputs into the environment. This chapter describes and assesses different agricultural and environmental policy instruments and measures for enabling sustainable nitrogen use. Effective agricultural and environmental policies must ensure that all the stakeholders are able to plan for the long term. It is also necessary to consider the wider sustainable agricultural context, since a reduction in nitrogen inputs has implications for certain aspects of animal welfare, climate change and biodiversity. Regional and local ecosystems and habitats that are particularly threatened must be effectively protected against excessive nitrogen inputs, while considering the specific site conditions, pre-existing nitrogen load and vulnerabilities. Consequently, in order to address the key challenge posed by this acatech POSITION PAPER ("How can agricultural nitrogen inputs into the environment be reduced?"), it will be necessary to manage overall nitrogen levels while also taking local requirements into account.[117]

4.1 Sustainable management structures

4.1.1 Conditions in the livestock farming industry

The concentration of livestock farming in certain German regions means that these parts of the country have very high nitrogen surpluses due to the high local levels of farm manure, predominantly in the form of liquid manure, which is often referred to as slurry (see also Chapter 3.3). Between 2009 and 2018, livestock densities and the associated nitrogen levels rose even further in northwest Germany, whereas they remained largely stable or declined in other parts of the country (see Figure 8).[118] The current conditions in the livestock farming industry are failing to adequately counteract this undesirable livestock concentration trend.

The practice of transporting farm manure from areas where there is a surplus to neighbouring regions has contributed to rising nitrogen surpluses in these regions.[119] Since liquid manure is mostly water, the extra transport requirements associated with its volume and weight mean that sending it to other predominantly arable regions has economic and environmental drawbacks in the shape of additional costs and CO_2 emissions. While it is possible to concentrate the nutrients in liquid manure by removing the water, this is a very energy-intensive process that only has a limited impact on the economic and environmental problems of inter-regional transport.

The same applies to digestate, which is often associated with intensive livestock farming regions, since liquid manure is a key biogas substrate. Liquid manure accounted for over 40% of the total substrate used in 2016 – around 30% of the 160 million metric tonnes of liquid manure produced in Germany was used for this purpose.[120] During fermentation, organically bound nitrogen in the liquid manure is partly converted into ammonium. This becomes available to plants more rapidly after application, but also means that potentially harmful emissions can escape into the environment more easily. Since almost all of the nitrogen in the substrate remains in the digestate, biogas plants do not help to reduce nitrogen surpluses. Other nitrogen-related impacts of biogas plants are highly dependent on how the plants are integrated into agricultural systems. Key factors include the types of substrate fermented and the availability of sufficient farmland and grassland to efficiently utilise the digestate produced by the plant.

One solution that addresses the underlying structure of the livestock farming industry is to close nutrient cycles by returning to the practice of carrying out crop cultivation and livestock farming in the same areas. This can help to reduce local surpluses. In addition to greater decentralisation of livestock farming, lower livestock densities in general would also have a direct impact

117 | See Möckel/Wolf 2020.
118 | See Häußermann et al. 2019.
119 | See ibid.
120 | See Scholwin et al. 2019.

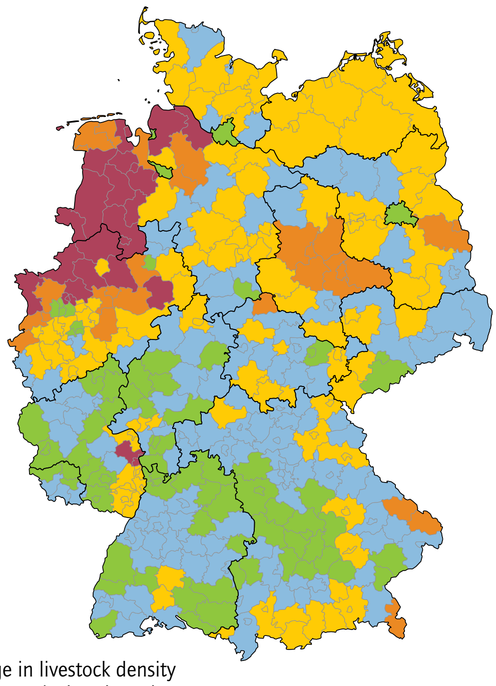

Figure 8: Changes in livestock density based on the averages for 1995–1997 and 2015–2017 (Source: Häußermann et al. 2019)

on nitrogen surpluses in the German agricultural sector. As well as addressing the problem of nitrogen emissions from livestock farming, reducing the number of livestock units in existing housings would also have benefits for animal welfare and food safety (by reducing the likelihood of zoonotic diseases).[121]

One instrument for addressing the highly concentrated nature of the livestock farming industry would be the introduction of a livestock-to-land ratio (German: Flächenbindung). This measure, which has been discussed for some time,[122] could help to significantly reduce the nitrogen surplus.[123] In several federal states, subsidies for new animal housings already stipulate a limit of two livestock units per hectare. A nationwide livestock-to-land ratio that establishes an upper limit – as announced in 2016 in the Climate Action Plan 2050[124] and as currently being discussed by the German government that took office in 2021[125] – could act as a strong incentive. In order to account for variation in site conditions, e.g. with regard to natural habitat vulnerabilities, this nationwide livestock-to-land ratio could be accompanied by specific regional recommendations or regulations with limits of less than two livestock units per hectare. Yield potential (determined by soil and weather conditions) is an important consideration in this context. For instance, the vegetation in productive grasslands such as the Alpine foothills can take up and utilise higher quantities of nitrogen than crops grown on sandy soil in places like Brandenburg, which have lower yield potential and cannot convert as much nitrogen. Since the nitrogen inputs in areas like this should be correspondingly lower, it makes sense for them to have a lower regional livestock density.

The introduction of limits on livestock density would require farmers to provide proof that they are using a sufficiently large area of their farm's own land or cooperating with other farms to ensure that the necessary land is available. This should have the effect of increasing demand for land with low stocking densities, especially outside of the regions that currently have high densities. It should also drive up the price of manure sold to other farms. This would make intensive livestock farming less profitable and create a targeted incentive to increase the number of livestock farms in regions with a lower stocking density.

Statutory regulation of a livestock-to-land ratio must address the protection of legitimate expectations and grandfather clauses for existing livestock facilities. Regulations stipulating mandatory removal or conversion of housings can only be implemented if they are supported by financial compensation for investments that have not yet been amortised. Consequently, as discussed in the debate on animal welfare, the best option from both a policy and a regulatory perspective may be the voluntary removal or conversion of existing housings. This could potentially be financed through a nationwide animal welfare tax on animal food products (see Chapter 4.2.1).[126] This would result in fewer animals being kept in existing housings, thereby reducing the stocking density provided that new housings were not built to

121 | Zoonotic diseases are diseases that can be transmitted from animals to humans, as happened with the SARS-CoV-2 virus. Swine influenza is also particularly relevant in the European livestock farming sector, see Henritzi et al. 2020.

122 | See Gesetzesantrag des Landes Niedersachsen 1994.

123 | See Häußermann et al. 2019.

124 | See BMU 2016.

125 | See SPD/Bündnis 90/Die Grünen/FDP 2021.

126 | See Kompetenznetzwerk Nutztierhaltung 2020.

compensate. A comprehensive impact assessment found that implementing the proposed animal welfare measures could result in major changes for individual farms and for the development of the entire livestock farming industry in Germany.[127] The introduction of additional animal welfare regulations will drive up production costs, although the extent of the increase will be different for different species and will depend on some key aspects of the regulations that have yet to be specified, such as the outdoor exercise area per livestock unit. Financial assistance can mitigate the cost impacts, helping to prevent the relocation of production to countries with less stringent regulations (see Chapter 4.2.1). This would allow farmers to plan for the long term and support the profitability of farms with livestock.

4.1.2 Changing farming practices to reduce the nitrogen surplus

Different elements of current organic and conventional farming practices can be combined to create a sustainable farming system that includes a range of different farming methods.[128] This also applies to the adaptation and sustainable use of technologies such as breeding techniques (see Chapter 4.3.1).

Organic farming is often more nitrogen-efficient than conventional farming,[129] even when accounting for the fact that, depending on the context, organic farming yields can be anywhere between 3% and 53% lower.[130, 131, 132] The lower nitrogen surpluses on organic farms and the fact that nitrogen losses are 28%–39% lower[133] are a direct consequence of these farms' limited nitrogen use – the use of mineral fertilisers is not permitted on organic farms,[134] while the sourcing of animal feed, biomass and organic fertilisers is regulated. Other contributory factors are organic farms' management standards, diverse farm structures and diversified crop rotation including legumes, undersown crops, and catch crops. The livestock-to-land ratios on organic farms also contribute to low nitrogen surpluses. Landless livestock production is prohibited in organic farming. While the EU regulations establish a maximum stocking density of two livestock units per hectare,[135] organic farming associations in Germany have adopted a lower limit of 1.4 livestock units per hectare. Accordingly, organic farms are mostly low-input systems as far as nitrogen is concerned, and nitrogen is often a yield-limiting factor.

The German government wishes to increase organic farming's share of agricultural area from its current level of around 10% to 30% (approximately 5.4 million hectares) by 2030.[136] The rapid rise in sales of organic products is another factor driving a substantial increase in the area of land devoted to organic farming. The European Commission's 2020 Farm to Fork Strategy establishes a target of 25% of agricultural land under organic farming. As with conventional farming, the nitrogen balance and environmental impacts of organic farming are influenced by site conditions, and this must be reflected in organic farming subsidies.[137] Faster growth of the organic farming sector will have both positive consequences (e.g. lower nitrogen surpluses) and negative impacts (e.g. lower yields). Consequently, organisations including the Scientific Advisory Board on Agricultural Policy, Food and Consumer Health Protection (WBAE) recommend a comprehensive, ongoing assessment of the impacts of the growth in organic farming.[138] Because it produces lower yields, the goal of expanding organic farming should be combined with (a) measures to reduce food waste and (b) measures to reduce animal food product consumption (see Chapter 4.4).[139] However, if these lower yields are not accompanied by a reduction in domestic food product consumption, the goal of increasing organic farming could actually prove to be counterproductive at a global level if it leads to more net agricultural product imports from countries with lower animal welfare and sustainability standards.[140] This could result in more land being used for agricultural production, for example.

127 | See Deblitz et al. 2021.
128 | See acatech 2019.
129 | See Sanders/Heß 2019.
130 | See Haller et al. 2020.
131 | See WBAE 2016.
132 | See Seufert et al. 2012.
133 | See Sanders/Heß 2019.
134 | See Regulation (EU) 2018/848 2022, Art. 9 and Annex II, Section 1.9.8.
135 | See implementation rules in Commission Regulation 889/2008, Arts. 15 and 16.
136 | See SPD/Bündnis 90/Die Grünen/FDP 2021.
137 | See WBAE 2020.
138 | See ibid.
139 | See Muller et al. 2017.
140 | See acatech 2020.

4.2 The economic and regulatory framework

4.2.1 Internalising the external costs of nitrogen surpluses

At present, the external (environmental and economic) costs of nitrogen inputs into the environment are not internalised, i.e. they are not reflected in the price of agricultural products or borne by the businesses responsible for them. Instead, these costs are borne by society and future generations. The approach to external costs affects many different aspects of agriculture, as illustrated by the debates concerning the use of plant protection products,[141] the financing of livestock farming with high animal welfare standards[142] and greenhouse gas emissions.[143] This section does not attempt to discuss the inclusion of agriculture in the pricing of greenhouse gases such as CO_2 along the lines of the regulations in other sectors, since this is a highly complex issue that only partly overlaps with this paper's focus on nitrogen.[144] The high level of animal product exports contributes to the high nitrogen surplus, since feed is simultaneously being imported from abroad and the resulting manure remains on German farmland. These exports are indirectly subsidised due to inadequate regulation and the failure to internalise the external costs to society, which originate from their contribution to the nitrogen surplus.

This problem could be counteracted either through the direct pricing of nitrogen surpluses or the pricing of mineral nitrogen fertilisers and bought-in animal feed. This would create economic incentives to use fertiliser and feed more efficiently and prevent nitrogen inputs into the environment, thereby also reducing the external consequential costs. Moreover, pricing – even as a flat-rate tax – would ensure that the external costs of nitrogen emissions and inputs into the environment were at least partly incorporated into farmers' cost calculations and product prices. The revenue raised from pricing could be used to cover the remaining consequential costs to society, e.g. for drinking water treatment or nature conservation measures. There have been calls for pricing strategies along these lines for many years[145, 146] and this approach was recently cited as an option by the Commission on the Future of Agriculture.[147] In addition to different pricing strategies, funding – e.g. through the Common Agricultural Policy (CAP) pillars – can also be used to promote nitrogen-efficient agriculture. One important general advantage of pricing is that, regardless of which specific form it takes, it gives farms the entrepreneurial freedom to decide which measures they employ to achieve sustainable nitrogen use. Pricing strategies should take into account their impact on competitiveness (see the section on competitiveness and the use of revenue from pricing in this chapter) and the effects of major fluctuations in the market price of agricultural inputs, as recently witnessed when mineral fertiliser prices rose sharply in 2021 and 2022.

Nitrogen surplus levy

Farms could be charged a nitrogen surplus levy, with its level determined by nitrogen balance accounting (see the panel on calculating fertiliser requirements and nitrogen balance accounting in Chapter 4.2.2). Some farms have already been carrying out such accounting since 2018 under the Nitrogen Balance Budget Ordinance (see Chapter 4.2.2).[148] Farms with high numbers of livestock and a high stocking density must provide a detailed record of their nutrient inputs and outputs. All farms with more than 50 livestock units or over 30 hectares of agricultural area and a stocking density above 2.5 livestock units per hectare must produce a nitrogen balance budget. Farms that use bought-in manure on the land or in a biogas plant are also required to produce budgets. In January 2023, the requirement to produce a budget was extended to all farms with more than 20 hectares of agricultural area.

141 | See Möckel et al. 2021.
142 | See Kompetenznetzwerk Nutztierhaltung 2020.
143 | See Isermeyer et al. 2019.
144 | As well as nitrous oxide emissions, methane emissions from cattle and soil carbon storage are particularly important in this context. However, nitrogen also has impacts on biodiversity that are not taken into account by greenhouse gas pricing. Further reading (ibid.) is recommended for a detailed discussion of the inclusion of farming in greenhouse gas pricing.
145 | See WBAE 2016.
146 | See Der Rat von Sachverständigen für Umweltfragen 1985.
147 | See Zukunftskommission Landwirtschaft 2021.
148 | See Taube et al. 2020.

The level of the nitrogen surplus levy could be determined by establishing a threshold above which farms would be charged for every kilogram of surplus nitrogen.[149] Setting the threshold and levy rate per kilogram at the right level is key to the levy's effectiveness as a financial incentive for farms to reduce their nitrogen surplus.[150] In contrast to the pricing of mineral fertilisers and bought-in animal feed, the revenue from a nitrogen surplus levy would be close to zero if almost nobody exceeded the threshold anymore.

One advantage of a nitrogen surplus levy is that it is based directly on surpluses in the nitrogen budget which reflect the level of inputs into the environment. Unlike the pricing of agricultural inputs at "bottlenecks" (see next section), a nitrogen surplus levy on farms would allow for regional or farm-level differences in the threshold and levy rate, along the same lines as property taxes. This would make it possible to reflect ecological differences e.g. with regard to soil type, precipitation and vulnerable ecosystems, habitats and species.

Compared to pricing at agricultural input bottlenecks as described in the next section, the drawbacks of a nitrogen surplus levy include higher administrative requirements and costs, since it would be necessary to audit the nitrogen budgets of over 200,000 farms. As a result, the advisory board of the Federal Ministry of Food and Agriculture (BMEL) does not recommend a nitrogen surplus levy.[151] However, the administrative burden of a nitrogen surplus levy would only be slightly higher if all farms were already legally obliged to produce budgets and these were already being audited. While the Nitrogen Balance Budget Ordinance currently only requires this of certain farms, the number of farms obliged to produce budgets increased significantly in January 2023 (see above). In this scenario, there are only slightly higher administrative burdens for the farms themselves.[152]

Pricing of mineral fertilisers and bought-in animal feed

The pricing of fertilisers at "bottlenecks"[153] focuses on the companies that market mineral nitrogen fertilisers. Bottlenecks are points in the value chain that large numbers of goods pass through, such as large enterprises or government agencies. There are just a handful of companies that produce or import mineral fertilisers and market them in Germany.[154] It is estimated that a tax of €0.50 per kilogram of mineral fertiliser would reduce its use by 11%.[155] Other countries have demonstrated that a tax can reduce fertiliser use. For instance, fertiliser use in Austria fell by 3% a year between 1986 and 1994 following the introduction of a nitrogen tax that increased fertiliser prices by 10%.[156] The tax was abolished when Austria joined the EU due to fears that it would put Austrian farmers at a competitive disadvantage compared to other EU members.[157]

The advantage of a mineral fertiliser tax over a nitrogen surplus levy (see previous section) is that it would be easier to collect and manage. It is also likely that a tax on mineral fertilisers would cause farmers to use them more efficiently and would increase the value of farm manure; in 2020, mineral fertilisers were responsible for approximately 48% of nitrogen inputs from agriculture in Germany.[158] In view of the regional concentration of livestock farming in Germany, the extent to which a tax would result in a wider geographical distribution of farm manure is not entirely clear.[159] Excrement disposal is currently a cost factor for the majority of landless livestock farms. Moreover, a tax on mineral nitrogen would not reflect regional differences, and would increase the price of fertilisers in general rather than only pricing nitrogen surpluses. The less targeted nature of such a tax would be a significant drawback compared to a nitrogen surplus levy, especially in the current context of high energy and fertiliser

149 | See Möckel 2017.
150 | See Oehlmann et al. 2018.
151 | See WBAE 2016.
152 | In order to ensure effective implementation of a nitrogen surplus levy, the exact nature and extent of the auditing mechanisms would need to be carefully defined.
153 | See Möckel 2006.
154 | See Isermeyer et al. 2019.
155 | See Grethe et al. 2021. It should be noted that a tax would increase the price of mineral fertilisers by the same amount for all the affected farms. In other words, there would be some farms and crops for which a tax of €0.50 per kilogram of mineral fertiliser would be sufficient to create the desired incentive, whereas for other farms and crops €0.50 would be far too low to be effective.
156 | See WBAE 2016.
157 | See Möckel 2017.
158 | See BMEL 2022b.
159 | See Isermeyer et al. 2019.

prices. It is also unclear whether only taxing mineral fertilisers could create an indirect incentive to keep more livestock, resulting in higher animal feed imports.[160]

Bought-in animal feed is also a source of farm nitrogen surpluses [161] and should therefore be included in tax-based solutions in order to create a financial incentive to reduce both of the key nitrogenous inputs, i.e. mineral fertilisers and animal feed.[162] Feed produced and used internally on farms would be exempt from this tax. The level of the tax on mineral nitrogen fertilisers and bought-in animal feed should be determined by their nitrogen content. The tax could also reflect the content of other fertiliser components such as phosphorus. While animal feed importers and agricultural wholesalers constitute "bottlenecks", farms can also sell feed directly to neighbouring livestock operations.[163] If the farm selling the feed takes the livestock manure back from the neighbouring farm, the nitrogen cycle is closed and the feed can be categorised as having been produced and used internally. The recording and differentiation of direct feed sales would make the auditing process and administration of the tax somewhat more complicated. However, examples in other areas such as taxes on alcohol suggest that it would still be practicable.

A flat-rate tax on all animal feeds should not penalise farmers for feeding by-products from the processing of domestic crop products, such as bran and draff, back into the agricultural cycle, since this practice is desirable from a sustainability perspective. By-products could be exempt from the tax in order to support circular management practices.

Competitiveness and the use of revenue from pricing

If pricing of nitrogen or nitrogen surpluses is only introduced in Germany, German farms could find themselves at a disadvantage compared to their international competitors. Consequently, any regulations should, as far as possible, apply to the whole of the EU. If the relevant measures are only implemented in Germany, a repayment of some of the revenue could help to mitigate the negative impacts on German farms' international competitiveness. If national regulations help to establish functioning, sustainable nitrogen use and reduce nitrogen inputs in the German agricultural sector, this could encourage other countries to follow suit. However, poorly conceived measures could result in leakage, i.e. the relocation of agricultural production to countries with lower standards.

How the revenue is used depends on whether it is raised in the form of a tax or a non-tax levy. The Federal Constitutional Court has ruled that, on the basis of the relevant provisions in Germany's Basic Law, the raising of revenue in the form of tax should be prioritised over the use of non-tax levies, and that the use of the latter shall require special justification.[164]

The obvious option for the pricing of mineral nitrogen fertilisers and/or bought-in animal feed would be a transaction tax on the trading of all bought-in fertilisers and feeds, since it could be easily related to a legal transaction (purchase).[165] This tax could be introduced at the federal level – pricing of bought-in fertilisers and feed should only be introduced for the whole of Germany in order to maintain the state's legal and economic unity. However, the revenue would accrue to the budgets of the federal states in accordance with Article 106 (2)(3) of Germany's Basic Law. Federal law would need to regulate how the revenue was split between the states, for example based on their share of Germany's agricultural area. The state legislators have control over their own budget and, as with all taxes, could therefore decide how to spend the revenue allocated to them.[166]

The Federal Constitutional Court has ruled that tax revenue may in principle be ring-fenced, provided that this does not unduly restrict the freedom of the budgetary legislator to determine how it is used.[167] This is unlikely to be an issue for taxes that only account for a small percentage of the overall budget.[168] Nevertheless, it would be necessary to ensure that any ring-fencing is compatible with international and European law. It is not clear whether ring-fencing of tax revenue might contravene European

160 | See Isermeyer et al. 2019.
161 | See Gawel et al. 2011.
162 | See ibid.
163 | See Isermeyer et al. 2019.
164 | For more details, see Möckel et al. 2015.
165 | See Möckel et al. 2021.
166 | See BVerfG 2 BvL 31, 33/56; BVerfG 1 BvL 1, 7/58; BVerfG 2 BvR 154/74.
167 | See BVerfG 2 BvR 413/88 and 1300/93; BVerfG 1 BvR 1748/99, 905/00.
168 | For more details, see Möckel et al. 2015, pp. 266–272.

state aid law: conflicts could arise if foreign fertiliser and feed producers or merchants who exported these products to Germany were required to pay the same tax as German merchants, but the revenue was only used to benefit German farms. On the other hand, as with all taxes and levies, the revenue could simply accrue to the national budget without being ring-fenced, provided that the tax is non-discriminatory, i.e. as long as the same tax scale and rate apply to foreign and domestic products. A detailed assessment of the legality of ring-fencing is thus essential. The revenue from a tax could be used to support sustainable nitrogen use, for example by promoting changes in agricultural practices or technologies, or funding professional development and environmental consultancy services for farms.

A nitrogen surplus levy could not raise revenue in the form of the taxes listed under Article 106 of the Basic Law.[169] Instead, it would most probably function as a special financing levy (German: Finanzierungssonderabgabe) as recognised by the Federal Constitutional Court.[170] The court has established certain eligibility requirements for this type of levy, for example with regard to the collective responsibility of those liable to the levy and the use of the revenue to benefit particular groups.[171] There are two main options for using the revenue to benefit particular groups. The first is to pay a rebate to all farms, regardless of their nitrogen surplus, for example based on the area of farmed land. This would mean that, as well as farms with high nitrogen surpluses that had to pay the levy, the rebate would also be paid to farms with lower nitrogen surpluses that had not paid the levy. The advantage of this model is that pricing would not take any money out of the agricultural sector as a whole, making it easier to implement politically and potentially reducing leakage. If this policy option is implemented, it would be important to check whether it might have any other undesired effects. If the rebates are based on the area of farmed land, they would reward land ownership, as currently happens with the first pillar of the Common Agricultural Policy (CAP). This would give farmers an incentive to increase the size of their farms, which could have effects such as further increases in lease prices.

Another option would be to use the revenue to finance measures to reduce farms' nitrogen surpluses or to mitigate and remediate the impacts of agricultural nitrogen inputs into the environment. Possible measures include funding changes in agricultural practices and technologies or professional development and environmental consultancy services for farms, drinking water treatment, or agri-environmental measures to reduce nitrogen. This would help to partly offset the costs to society of nitrogen inputs in accordance with the polluter pays principle, while using the revenue for ecological purposes would provide financial support for the goal of sustainable nitrogen use. This second option would also meet the requirement to use the revenue to benefit particular groups, since it would be used to address the collective responsibility as polluters of farms that generate nitrogen emissions.[172] European state aid law would also be complied with provided that the agri-environmental measures were implemented under the second pillar of the Common Agricultural Policy (EAFRD Regulation).

Common Agricultural Policy funding for farms

Because it largely involves area-based direct payments, the funding provided to farms through the EU's Common Agricultural Policy (CAP) (see Chapter 2) has hitherto done very little to address the agricultural sector's negative environmental impacts.[173, 174] The new rules in the reformed CAP, which are due to come into force between 2023 and 2027, only slightly reduce the proportion of area-based direct payments. In view of the current climate and environmental protection targets, there have been widespread calls for direct payments to be largely replaced by payments rewarding environmental and climate protection measures at EU level.[175, 176, 177] This could be done if the next incarnation of the CAP only provided financial support for the current

169 | See BVerfG 2 BvL 6/13. The Federal Constitutional Court considers this list to be definitive, and maintains that the responsible legislator does not have the right to create new types of tax over and above those listed.
170 | For more details, see Möckel 2017, pp. 15–28.
171 | See BVerfG 2 BvR 1139/12; BVerfG 2 BvF 3/77.
172 | For more details, see Möckel 2017, pp. 77, 92–94.
173 | See Pe'er et al. 2020.
174 | See Europäischer Rechnungshof 2021.
175 | See Pe'er et al. 2020.
176 | See Europäischer Rechnungshof 2021.
177 | See Leopoldina/acatech/Akademienunion 2020.

second pillar and the mechanisms that it contains for funding appropriate measures. This change would also make a significant contribution to sustainable nitrogen use in agriculture.

At national level, in April 2021 the German cabinet approved the implementation of four laws that will form the basis of Germany's national CAP strategic plan, according to which 25% of direct payments must be linked to environmental and climate protection measures (eco schemes or eco regulations). The extent to which these measures contribute to reducing the nitrogen surplus varies, with farms able to choose from a range of different measures to reduce nitrogen inputs into the environment. Arable farms can opt to grow a diverse range of crops, including legumes, and can also implement land set aside and grassland extensification measures. However, the eco schemes currently lack ambition.

Another option for promoting the reduction of nitrogen surpluses would be to reallocate funds from the first to the second pillar of the Common Agricultural Policy (CAP). Germany's federal states could also make more funding available for agri-environmental measures to reduce nitrogen. Historically, just 6% of funds have been reallocated from the first to the second CAP pillar across Germany as a whole, but this figure is due to rise to 10% in 2023 and will then gradually increase to 15% by 2026.[178] Implementation of the management measures in the second pillar is voluntary and EU rules state that they may not be used to make a profit. Nevertheless, the reallocation of more funds would provide a broader funding base for environmental protection measures in the agricultural sector and could be combined with the other measures discussed above, i.e. a tax on mineral fertilisers and bought-in animal feed or a nitrogen surplus levy.

Consumer/product taxes

Reforms in the livestock farming industry are key to achieving sustainable nitrogen use in agriculture and are also important from an animal welfare perspective (see Chapter 4.1). The Animal Husbandry Competence Network (German: Kompetenznetzwerk Nutztierhaltung), also known as the Borchert Commission, has proposed a number of financial instruments for promoting animal welfare.[179] The final report of the Commission on the Future of Agriculture also highlights the importance of these proposals.[180] The proposed financial instruments are targeted at consumers: the experts of both commissions recommend either changing the V.A.T. rate or introducing a quantity tax on animal products, technically implemented as a consumption tax. A feasibility study evaluating the practicability of these measures was published at the beginning of March 2021.[181] According to this study, raising the discounted V.A.T. rate for animal products would have the advantage of being easy to implement from an administrative perspective. Increasing the V.A.T. rate results in a percentage increase in prices. This means that the absolute price rise would be higher for sustainably produced animal products that are already more expensive than for other, cheaper products, potentially causing demand for sustainably produced products to decline. This effect would not occur with a quantity-based consumption tax, since the prices for a given product category would all increase by the same amount.[182] As a result, this type of tax would be a more effective means of achieving the desired changes in consumer behaviour. Imported goods would also be taxed under both options. This would raise questions regarding the permissibility under EU state aid law of ring-fencing revenue from a quantity tax for use in the German agricultural sector, potentially to fund higher animal welfare standards or environmental and climate protection measures.[183] It would also be necessary to consider how both options can be supported through social policy measures.

178 | See BMEL 2021a.

179 | See Kompetenznetzwerk Nutztierhaltung 2020.

180 | See Zukunftskommission Landwirtschaft 2021.

181 | See Karpenstein et al. 2021.

182 | For instance, the Animal Husbandry Competence Network (German: Kompetenznetzwerk Nutztierhaltung) believes that it would be feasible to introduce a tax of €0.40 per kilogram of meat and processed meat products, €0.02 per kilogram of milk, fresh milk products and eggs, and €0.15 per kilogram of cheese, butter and powdered milk, see Kompetenznetzwerk Nutztierhaltung 2020.

183 | See Karpenstein et al. 2021.

4.2.2 Farm nutrient management

Consistently high nitrogen surpluses over several years have led to increasingly strict regulation of nutrient management and fertilisation practices. The rules on nitrogen fertilisation are set out in the Fertiliser Act (German: Düngegesetz) and more specifically in the Fertiliser Ordinance (German: Düngeverordnung – DüV), as well as in the Nitrogen Balance Budget Ordinance (German: Stoffstrombilanzverordnung – StoffBilV). The amended Fertiliser Ordinance came into force in May 2020 and has been fully applicable since 1 January 2021.

Until 2020, the Fertiliser Ordinance used a "nutrient comparison" (German: Nährstoffvergleich)[184] to determine the nutrient surplus of agricultural area. The Nitrogen Balance Budget Ordinance came into force on 1 January 2018 with the aim of making farm nitrogen balance more transparent in order to reduce nutrient losses from agriculture and ensure that environmental targets are met. In nitrogen balance budgets, farms document nitrogen inflows and outflows based on the "farm gate" principle (see panel on calculating fertiliser requirements and nitrogen balance accounting). Nitrogen balance accounting is being phased in gradually.

The current nitrogen balance accounting rules suffer from a number of weaknesses that undermine their effectiveness.[185] To begin with, the rules apply to far fewer farms than the area-based nitrogen balance accounting system that existed pre-2020, although the requirement to produce a budget is being extended to smaller farms from January 2023.[186] Furthermore, there are no effective mechanisms for sanctioning farms that exceed the upper limits stipulated in Section 6 of the Nitrogen Balance Budget Ordinance. Moreover, experts have questioned the scientific validity of some of the nutrient requirement values that the ordinance is based on.[187] They argue that the nutrient requirement values used are higher than the actual nitrogen requirements of the relevant crops, thereby legitimising the application of "surplus" nitrogen that ends up in the soil and the environment. They also maintain that the permissible nitrogen balance budget of 175 kilograms of nitrogen per hectare – i.e. the maximum allowable nitrogen surplus – is too high to effectively reduce inputs into the environment.[188]

In agricultural practice, there is some variation in the nitrogen content of farm manure and biogas plant digestate and in soil nitrogen content. The nitrogen content values depend on the animal feeding and fertilisation practices of individual farms. The ordinance currently uses approximate values. However, the values for manure and soil could be determined precisely in cooperation with the federal states' agricultural research institutes, thereby ensuring that the values used in the calculations are evidence-based. This would make it possible to reflect nitrogen mineralisation from the soil after long-term liquid manure application, for example.

In addition, the nationwide nitrogen balance accounting rules and budget limits fail to reflect regional and local differences. The accounting system does not adequately take account of regional climatic conditions and soil properties or their relevance to climate protection and air and water quality. For example, the impact of nitrogen surpluses on the concentration and quantity of nitrogen in runoff and thus on groundwater nitrate content varies depending on soil type, soil depth and annual precipitation. The lower groundwater recharge rate in areas with low precipitation means that even relatively small nitrogen surpluses lead to high runoff nitrate concentrations, with the result that the 50 mg of nitrate per litre of groundwater limit is exceeded comparatively faster. The evaluation of the Nitrogen Balance Budget Ordinance due to conclude by the end of 2021 provides an opportunity to address these weaknesses.

184 | See DüV 2017, Arts. 8, 9.

185 | See Taube et al. 2020.

186 | Since 2018, all farms with more than 50 livestock units or over 30 hectares of agricultural area and a stocking density of more than 2.5 livestock units per hectare have been required to produce a nitrogen balance budget. Farms that use bought-in manure on the land or in a biogas plant are also required to produce budgets. From 2023, the Nitrogen Balance Budget Ordinance will be extended to all farms with more than 20 hectares of agricultural area.

187 | See Taube et al. 2020.

188 | The nitrogen balance budget is calculated as the sum of all nutrient flows and thus determines the maximum permissible nutrient surplus.

Calculating fertiliser requirements and nitrogen balance accounting

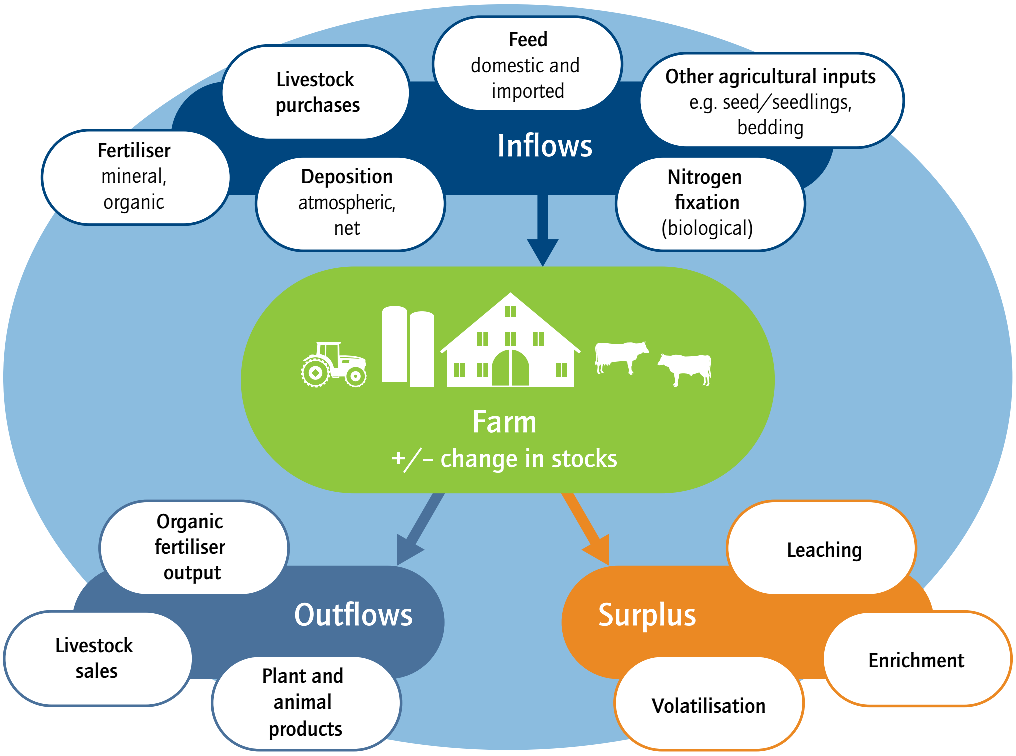

Figure 9: Key elements of nitrogen balance accounting (Source: authors' own illustration based on Klages et al. 2017)

Farms draw up a fertilisation plan based on their calculations of how much fertiliser is needed by different crops to achieve a given yield. Nutrient management and fertilisation practices are regulated by the Fertiliser Ordinance (DüV), which stipulates that the annual fertiliser requirement must be calculated using an accounting system. Every crop plant has different nutrient requirements. In practice, it is necessary to estimate the likely (target) yield by calculating the average yield for the last five years.

Soil properties should ideally be taken into account when calculating the target yield and fertiliser requirements. These can vary even within an individual plot. In practice, this means that the crop plants in the most favourable locations grow better and thus take up more nutrients than those in less favourable locations. Nitrogen crop fertilisers are mostly applied in spring, with the exact timing depending on the weather, crop development and the different crop growth phases. To calculate the fertiliser requirements, it is necessary to record and document the specific management unit, specific crop, and the fertiliser type, quantity and application method.

A nitrogen balance budget based on the "farm gate" principle reflects all of a farm's nutrient inflows and outflows from agricultural inputs, animal feed and agricultural products (see Figure 9). It documents the nutrient inflows from feed and fertiliser, seed, livestock purchases and legume nitrogen fixation. This is then set off against the nutrient outflows in the form of animals, plant and animal products, fertiliser and seed. The balance for both nitrogen and phosphorus must be documented with delivery notes or invoices. Dividing the overall result of the nitrogen balance budget by the area of the farm's agricultural land gives the average nutrient surplus per hectare. When calculating the nitrogen balance budget, it is necessary to make assumptions about the nitrogen content of agricultural products. The values used should reflect conditions on the farm as accurately as possible. For livestock farms and biogas plants, the nitrogen content of the animal feed or substrate and of the output manure or digestate is also extremely important. To enable accurate nitrogen balance accounting, it is vital to determine the values for these individual components of the budget in a scientific manner that reflects reality as closely as possible.

The nitrogen balance budget does not reflect internal nutrient flows and differences in nutrient management within a farm or the nitrogen surpluses of different parts of the farm. Even if the overall nitrogen balance budget is balanced, specific areas within a farm can still have high nutrient surpluses, especially in large farms and farms with significant soil property variation. Although calculating budgets for specific areas means more work for the farm, it provides more detailed information about how management practices can be optimised (see Chapter 4.3.1). In other words, while the calculation of budgets for specific areas improves operational knowledge, it is difficult to manage from an administrative perspective.

Fertiliser Ordinance rules for fertiliser application

As well as the calculation of fertiliser requirements and thus the maximum permissible quantity of fertiliser, the Fertiliser Ordinance regulates fertiliser storage and the times when fertiliser may or may not be applied. It also contains standards for minimising fertiliser application losses, e.g. during liquid manure application. Restrictions on the times when fertiliser may be applied are primarily based on plant growth, nutrient requirements and weather conditions. There is a general ban on the use of nitrogen fertilisers in winter during the dormant period/after harvesting. The regulations also take into account the cultivation of catch crops, the choice of winter crops and the type of fertiliser used. The 2020 amendment to the Fertiliser Ordinance introduced a number of new rules regarding the times when the use of fertiliser is prohibited.[189]

The Ordinance also regulates minimum distances from waterbodies (riparian buffer strips), although drainage channels and other small waterbodies are exempt in most federal states. However, there are no rules on minimum distances or buffer strips for nitrogen-sensitive terrestrial biotopes. German fertiliser law also fails to take into account the specific local soil, geological, topographical and climatic conditions, or the conservation status and vulnerability of local aquatic and terrestrial ecosystems and protected biotopes and species. The only exception relates to the designation of "red zones" for the protection of threatened groundwater and surface water bodies. Red zones are areas with high nitrate levels in groundwater bodies where there is a danger of surface water body eutrophication. In these zones, farms are only permitted to use a maximum of 80% (averaged across the farm) of the fertiliser requirement calculated in accordance with the Fertiliser Ordinance. In addition, no more than 170 kilograms of organic fertiliser per hectare per year may be applied to each field, cultivation unit or aggregated plot of arable land and grassland.[190]

189 | See LfL 2020a.
190 | See DüV 2020, Art. 3(2)(3).

4.3 Knowledge management and sustainable technology use

4.3.1 Potential for the sustainable use of technological innovations

Digital nutrient management and precision farming

Digital technology and automation can facilitate sustainable nitrogen use in agriculture. Precision farming is a targeted, spatially differentiated approach to farmland management. It enables precise fertilisation tailored to the requirements of individual subplots and supports more efficient use not only of nitrogen but also of other nutrients and plant protection products. Sensors in farm machinery and satellite-based remote sensing are used to measure parameters relevant to fertilisation such as the biomass yield, chlorophyll content, nitrogen content and nitrogen uptake of crop stands at defined development stages. This data can be used in conjunction with the relevant algorithms and models to describe soil properties, yields and nitrogen uptake in high spatial resolution, for example 10 x 10 metre squares, allowing nitrogen fertiliser requirements to be determined precisely at the subplot level.[191] Individual farms have limited capacity to carry out the knowledge and data management operations required to use these technologies.[192] Consequently, the shared use of digital technology by multiple farms is becoming increasingly important.

Agricultural machinery manufacturers and producers of fertiliser and plant protection products are constantly working to develop even better sensor-based fertilisation technology, fertilisation algorithms and digital fertilisation systems. There is also significant potential for further developments in the field of applied research. In addition to yield optimisation, fertilisation algorithms could also calculate the risk of nitrate leaching in a given area, for example. There is particular potential to optimise the way that fertilisation algorithms reflect small-scale soil property variations within the same field. This would help to prevent over-fertilisation by enabling more accurate estimates of a crop's nitrogen uptake capacity, which is highly dependent on local yield potential.

For all their promise, innovative technologies can only be used if certain basic requirements are in place. Rural areas often lack 4G or 5G coverage, yet this is essential for many precision farming and digital nutrient management devices and techniques. The high investment costs also constitute a barrier to the use of these technologies, especially for small and medium-sized farms. In addition to government support, other possible solutions include joint acquisition by producer associations or the use of contractors. These models are especially important in regions dominated by smaller farms. The use of digital technology also requires a certain level of user knowledge and training provision (see also Chapter 4.3.2).[193]

Good data management is key to ensuring that the captured data is used efficiently. The proliferation of different data tools and formats is currently still hindering the efficient exchange of operational data. Cross-system platforms can enable the exchange of data from systems made by different manufacturers. Sharing data and services securely and independently and optimising their use benefits farms, start-ups and medium-sized and large-scale enterprises alike. Various initiatives have already been launched in this area, including the Gaia-X AgriGaia project.[194, 195] Another issue is that differences in the implementation of the Fertiliser Ordinance and the relevant technical systems in Germany's federal states create inconsistencies that hamper the efficient development of widely usable data models. The adoption of a common approach by all the federal states would make it much easier to offer farms throughout Germany standard precision farming data models and would also facilitate these models' further development.

The "Bauernmilliarde" (farmer's billion) is a Federal Ministry of Food and Agriculture (BMEL) investment support scheme that subsidises up to 40% of the cost to farms of acquiring modern farming technology.[196] The current whitelist of eligible farming technologies includes low-emission application technologies. The programme's first round was heavily oversubscribed. This

191 | See Mittermayer et al. 2021.
192 | See Gandorfer et al. 2017.
193 | See ibid.
194 | See Plattform Lernende Systeme 2020.
195 | See BMWK 2022.
196 | See BMEL 2020a.

scheme could provide a blueprint for additional funding of nitrogen-efficient farming technology that also promotes compatibility between different agricultural manufacturers' machines and data management systems. Designing and implementing a programme of this type as a long-term measure would have the advantage of enabling more reliable forward planning for farms and the farming technology market.

Improving fertiliser application efficiency

The regulations on the incorporation of farm manure are geared towards reducing nitrogen emissions, especially ammonia emissions and the associated particulate pollution.[197] Since 2020, organic fertiliser applied to untilled arable land must be incorporated within four hours of spreading – and this period will be reduced to one hour from 2025.[198] An amendment to the relevant section of the Fertiliser Ordinance making immediate incorporation mandatory would help to further reduce ammonia emissions.[199]

While low-emission application technologies do already exist, their acquisition represents a substantial investment for farmers. The methods currently used in practice are liquid manure injection, drag hoses and the closed slot technique. In 2015, broadcasting was still used for 56% of liquid manure.[200] However, the use of this technique on tilled farmland has been prohibited since February 2020. After a transition period, this ban will be extended to pasture and multicut fodder crops from 2025. However, the Fertiliser Ordinance does not currently contain similar restrictions for untilled farmland. A general ban on broadcasting would help to reduce nitrogen emissions into the environment in the form of ammonia.

There is also room for improvement in the methods used to apply mineral fertilisers. Centrifugal spreaders are currently the most common application technology, accounting for 90% of the market in 2017. However, this technology is insufficiently precise around field margins and irregular field boundaries, where it results in the uncontrolled application of fertiliser to adjacent areas.[201] Centrifugal spreaders with boundary spreading limiters and machines with pneumatic spreading systems can help to address this problem. In the latter case, sensors can be used to facilitate precision fertiliser application, thereby helping to reduce nitrogen surpluses. However, pneumatic spreaders also have drawbacks; they have a lower ground coverage per pass than high-performance centrifugal spreaders, they are more expensive, and the technology is more complicated.[202]

Nitrogen inputs into the environment can also be reduced by using inhibitors. When added to fertiliser, these compounds slow down the rate at which the fertiliser is converted by soil organism enzymes. As with denitrification in general, the inhibitor's effectiveness is determined by soil microbial activity, which is heavily dependent on temperature and humidity.[203] In order to significantly reduce the release of ammonia from urea, since 2020 it has been mandatory to add urease inhibitors to mineral fertilisers with a urea content of 50% or more of the total nitrogen content and to urea ammonium nitrate solution unless they are incorporated into the soil immediately. Since the Fertiliser Ordinance currently exempts urea fertilisation on untilled farmland from this regulation, supplementary rules ending the exemption could help to further reduce emissions.

Nitrification inhibitors slow the oxidation of ammonium ions to nitrate, nitrous oxide or elemental nitrogen by inhibiting the activity of soil-borne bacteria. This means that fewer of these nitrogen compounds, especially nitrate, enter the environment and more ammonium is available to crops,[204] which in turn helps to maintain typical yields while reducing overall fertiliser use.[205] These positive impacts must be weighed up against the possibility of significant additional ammonia emissions,[206] the extent of which depends on soil pH and porosity. It is also necessary

197 | See Rösemann et al. 2019.
198 | See DüV 2020, Art. 6. Exemptions exist for solid manure from ungulates, compost and fertiliser with a documented dry matter content of < 2%.
199 | See WBA/WBD/SRU 2013.
200 | See Destatis 2020.
201 | See DLG 2017.
202 | See ibid.
203 | See Irigoyen et al. 2003.
204 | See Ruser/Schulz 2015.
205 | See Rose et al. 2018.
206 | Ammonia can be emitted into the atmosphere. Since the ammonia/ammonium content in the soil and the air are directly correlated, a higher soil ammonia content can result in higher losses to the atmosphere, see Lam et al. 2017.

to bear in mind that some traditional inhibitors may only break down slowly in the environment.[207] Innovative new products, including products of natural origin, are currently being developed to address this issue.

Significant quantities of nitrogen compounds, especially ammonia, also escape from livestock housing and from manure stored in the open air. Since 2017, Section 12 of the Fertiliser Ordinance has required farms to maintain a minimum manure storage capacity to store the manure that accumulates during the periods when fertilisation is not permitted. The aim of this regulation is to prevent the application of manure during these periods. Various livestock housing management practices relating to housing temperature and cleaning strategies can also help to reduce emissions.[208] Emissions vary depending on how livestock is kept – nitrogen emissions are somewhat lower for livestock kept in pasture than for livestock kept in open housings. Waste gas purification systems can be used in closed barns, but are expensive.[209] In some federal states, the use of these systems is mandatory for certain livestock species and housing types.[210] Gas-tight liquid manure storage tanks and closed housing systems can significantly reduce emissions and improve nitrogen use efficiency. The Administrative Regulation pertaining to the Federal Immission Control Act – known as the Technical Instructions on Air Quality Control (German: TA Luft) – is of particular relevance to the regulation of the required exhaust air treatment systems. After several years of preparation, the new version of the Technical Instructions on Air Quality Control was approved by the Federal Cabinet in June 2021. The revised regulations are extremely important for nitrogen emissions from livestock farming. For instance, large livestock facilities with more than 1,500 pigs or 30,000 broilers must now remove 70% of the ammonia/total nitrogen and particulate matter emissions from their exhaust air.[211, 212] The licensing process must consider nitrogen deposition in the area surrounding a facility, and a buffer zone of at least 150 metres must be maintained between the facility and any nitrogen-sensitive plants and ecosystems.[213]

Low-nitrogen feed and needs-based feeding

Livestock feed is another area where there is potential to reduce nitrogen inputs into the environment. At present, the quantity and amino acid composition of raw protein in livestock feed is often not well matched to the animals' requirements. In recent years, the protein requirements of different animals and their raw protein uptake from feed have been revised from a management practice perspective.[214, 215] This has opened the way to a lower-nitrogen, needs-based precision feeding approach based on supplementing animal diets with limiting essential amino acids. Precision feeding significantly reduces both manure nitrogen content[216] and overall livestock nitrogen excretion. Tailored diets also alter the composition of nitrogen excretions. For example, they can significantly lower ammonia emissions by reducing the amount of urea excreted. Precision feeding can thus help to reduce nitrogen surpluses and ammonia emissions, especially in regions with high liquid manure surpluses. More precisely tailored feed supplementation also improves animal welfare by lessening the strain on their metabolism. Farms can also benefit from lower costs – needs-based feeding leads to better protein uptake, meaning that less protein feed is required per livestock unit.

Precision feeding is not currently permitted on organic farms. The rules essentially ban organic farmers from supplementing animal diets with limiting essential amino acids, since the vast majority of these amino acids are produced with the aid of genetically modified microorganisms. The search for alternative sources of limiting essential amino acids has thus been a focus of organic animal husbandry research and practice for many years.[217, 218] Compared to farms that use conventional, low-nitrogen feed,

207 | See Scheurer et al. 2016.
208 | See LfL 2020b.
209 | There is a general conflict between the use of closed barns with exhaust air filters in order to reduce emissions and the importance of outdoor exercise for animal welfare. There is no obvious solution to this conflict in sight.
210 | See DLG 2018.
211 | See BMU 2021.
212 | See TA Luft 2021.
213 | See BMU 2021.
214 | See DLG 2019.
215 | See DLG 2020.
216 | See LfL 2021a.
217 | See Jakobsen/Hermansen 2001.
218 | See Zollitsch 2007.

significant deficiencies of essential amino acids in the feed used by organic farms can result in higher pig and poultry nitrogen excretions for the same stocking density and performance level. In other words, the nitrogen excretions and the associated ammonia emissions for a given quantity of animal food products from organic livestock farms can be higher than if systematic use is made of the relevant conventional animal feeding options.

Soil microbiome management

Targeted management of the microbiome, i.e. all the communities of microorganisms in the soil, is an emerging strategy for influencing biogeochemical cycles.[219] Fertiliser use can be optimised and nitrogen inputs into the environment reduced by altering the way that the microbiome utilises fertiliser. These changes can be promoted by altering the choice of crops in crop rotation systems or by inoculating the soil with microorganisms that possess the desired characteristics.[220] As well as changing the way that soil nitrogen is utilised, soil microbiome management can also reduce the use of plant protection products and improve soil health [221] and plant productivity.[222] The use of this technology is still in its infancy, and its effectiveness is influenced by various factors including crop rotation, soil properties and weather conditions.

Plant breeding methods

Breeding methods aimed at adapting plants to the increasingly pronounced impacts of climate change can also contribute to sustainable nitrogen use. Higher temperatures and extreme weather events such as heavy rainfall or severe droughts pose a serious challenge for farms and their productivity. If extreme weather causes crops to fail or seriously inhibits or delays their development, the applied fertiliser may not be taken up by the plants, resulting in a higher nitrogen surplus on the affected farmland. One solution is to breed nitrogen-efficient plants that are better at taking up and utilising nitrogen. Studies of rice, for example, have shown that plants engineered to have deeper roots or modified metabolisms are better at utilising lower levels of soil nitrogen.[223]

New molecular biology techniques such as CRISPR/Cas are expanding and accelerating the results that can be achieved using conventional plant breeding methods. While these techniques have huge potential in the food industry, their use in Europe has been held back by public opposition, since plants produced in this way are classified as genetically modified organisms.[224, 225] Consequently, a reform of the legal framework is key to enabling the use of breeding techniques to improve crop plant adaptation to climate change, although it will still be necessary to maintain the necessary transparency and safety standards.[226]

Food process and product innovations

Alternative protein products can help to reduce nitrogen surpluses, diminish the problems associated with intensive livestock farming and, in the long run, provide plant-based protein for a growing global population. Products made from sustainably produced pulses such as soybeans and peas can supplement or replace meat in our diet. Hybrid products with a reduced meat content are also now available. Recent years have seen improvements in the taste, sensory appeal and processing of plant-based products – these are all important factors for consumers when choosing meat substitutes.[227] Algae, fungi and insects are also possible sources of protein. These alternatives are promising in terms of sustainable nitrogen use, since they are mostly produced in closed production systems, meaning that hardly any nutrients can escape into the environment. Cell-based approaches where cultured meat is produced from animal cells offer similar benefits.[228] However, cultured meat is still technically challenging to produce, and its sustainability in highly scaled processes has yet to be demonstrated. It is thus necessary to weigh up all the different aspects of these processes before making a judgement about their potential sustainability benefits. The future

219 | See Qiu et al. 2019.
220 | See Hartman et al. 2018.
221 | See Dubey et al. 2019.
222 | See Saleem et al. 2019.
223 | See Liu et al. 2021.
224 | See acatech 2020.
225 | See Leopoldina et al. 2019.
226 | See ibid.
227 | See Rubio et al. 2020.
228 | See acatech 2020.

market success of these high-tech production processes could also be held back by consumer perceptions. The Federal Ministry of Food and Agriculture's 2021 Food Report found high overall levels of public interest in alternative protein sources; around one third of respondents said they already buy meat and dairy alternatives.[229]

4.3.2 Consulting, training and professional development for farmers

As with other aspects of agriculture, sustainable nitrogen use requires farmers to have a basic understanding of the ecological factors, the impacts of different land uses and management practices, and a knowledge of the current agri-environmental law requirements relating to the use of land for agriculture. A knowledge of the opportunities offered by new technologies such as digital solutions and other Agriculture 4.0 techniques is also set to become increasingly important. Consulting, training and professional development are key to sustainable farming in general and sustainable nitrogen use in particular. In the medium to long term, knowledge transfer from basic and applied research will also play a greater role, since it will be important to ensure that new developments are implemented as quickly as possible in practice.

Training and professional development

In Germany, vocational training for farmers is provided by certified training companies and vocational colleges, while universities and universities of applied sciences offer academic courses in agricultural science. Inevitably, this means that the scientific principles and practical applications e.g. of smart farming systems or organic farming are taught in a general manner. Education at every level now has to place greater emphasis on organic farming principles and methods and will in future also have to cover the opportunities of Agriculture 4.0. A knowledge of the correct way to use sustainable farming methods and technologies and of their environmental and economic benefits is key to the efficient and sustainable use of nitrogen in farming.[230] Content on nutrient management and the wider ecosystem impacts of nutrient use should form an integral part of training and professional development at every level. For instance, there should be more information about methods of green manuring with catch crops in order to promote their use and thus contribute to biodiversity conservation. Moreover, the agricultural sector's ever increasing social and legal responsibilities make it vital for farmers to keep updating their initial professional training through continuous professional development and lifelong learning. The growing knowledge management requirements will pose a particular challenge for smaller farms, especially those operated as a sideline.

Consulting and research

Independent information is vital to most farms, and agricultural consulting plays a key role in the transfer of knowledge into farming practice. A neutral, objective, public or publicly funded consulting service where the consultants have no personal financial stake is thus of paramount importance. The official government consulting service is a sovereign responsibility of Germany's federal states and is less well developed in some states than in others, with some services having suffered significant cutbacks in recent years. This means that the consulting provided by the state departments or chambers of agriculture is often not farm-specific and is frequently limited to general or regional recommendations for maintaining soil fertility and productivity. There is thus a strong need for official consulting services to provide farm-specific advice on both the economic and ecological dimensions of adapting management practices, crop rotation, tillage and fertiliser use. However, this would have to be funded and promoted by the federal states. One solution would be to use the revenue from a transaction tax on bought-in fertilisers and feed or a nitrogen surplus levy (see Chapter 4.2.1).

It makes sense for widely accessible, farm-specific consulting on nitrogen fertilisation and nutrient management to be provided through initiatives run by private institutions as well as through government agencies. Consulting platforms will play an important role in years to come, and must therefore be established, operated and maintained for this specific purpose. Platforms can effectively promote knowledge transfer and professional development by making it easy to access knowledge and exchange information about efficient nutrient management and the corresponding techniques (e.g. precision fertilisation and best practice examples from other farms). The state should therefore increase its support and funding for consulting platforms, especially those that enable communication between farms in the same region or local area with similar businesses and in situ

229 | See BMEL 2021b.
230 | See acatech 2020.

conditions. While a variety of different digital forums already exists, they rely on the engagement and financial contributions of their individual members. Public or publicly funded platforms could consolidate this knowledge sharing and make it more widely accessible.

Offering agricultural science students specialised courses on providing consulting could help to widen the pool of future consultants. In addition, government accredited or certified consultants who are required to engage in continuous professional development would help to ensure that up-to-date consulting is provided about constantly evolving fields such as digitalisation, data processing and sustainable farming practices.

Research has a key role in enabling sustainable nitrogen use in agriculture (see Chapters 4.3.1 and 4.3.2). Alongside further scientific development of nitrogen-efficient management methods and technologies, it is also vital to promote cooperation and communication between farms and researchers so that research findings are implemented promptly and in a targeted manner. There are already several ongoing projects on sustainable nitrogen management, animal welfare and digitalisation in the agricultural sector. Increasing the involvement of working farms in these activities, potentially also as demonstration farms, could help to promote wider implementation of modified management practices.

4.4 Sustainable consumption and informed purchase decisions

Unlike other issues such as organic farming, animal welfare and greenhouse gas emissions, there is still very little public awareness of the link between the food on our plates and the environmental impacts of nitrogen. Demand for sustainably produced food can be harnessed to also promote sustainable nitrogen use by combining consumer policy measures to reduce nitrogen with measures aimed at tackling negative environmental impacts in general. The consumption and product taxes discussed in Chapter 4.2.1 as a means of internalising external costs can also be regarded as consumer policy measures.

4.4.1 Sustainable consumption and preventing food waste

Retail chains respond almost instantly to changes in consumer behaviour and ultimately communicate customer wishes to producers via marketing companies. If customers are demanding more sustainably produced food, producers will soon take note and change their production methods. Credible, independent food product information that is intuitive to understand and highly visible to consumers increases the salience[231] of sustainably produced food at the point of sale and facilitates informed purchase and consumption decisions (see section on product labelling below). By demanding more organic products and consuming fewer animal products, consumers can indirectly influence the level of nitrogen inputs into the environment – provided that these choices also promote more generally sustainable production methods (see Chapter 4.1). Increased consumption of plant-based and other sustainably produced alternatives to animal products is also relevant in this context. More sustainable consumption can also be promoted in the communal catering facilities in company canteens, educational establishments and care facilities by ensuring that their menus place greater emphasis on sustainability. Since communal catering facilities serve approximately 16.5 million people a day in Germany,[232] they have significant potential for the sale of healthy, sustainably produced food. Canteens in workplaces and educational establishments are also a good place to inform consumers about the environmental and health impacts of different products. The state could set an example by developing standards for sustainable food procurement and catering, and implementing them in public communal catering facilities.

Preventing food waste is another important consumer measure that can help to cut nitrogen emissions and reduce some of the agricultural sector's other harmful environmental impacts. The Federal Ministry of Food and Agriculture's national strategy aims to halve food waste in the retail and consumer sector by 2030.[233] To do this, it will be vital to raise consumer awareness of the problem. Awareness campaigns such as "Zu gut für die Tonne" (Too Good for the Bin) encourage people to use food more carefully. Educational establishments for young people such as kindergartens and schools also have a role to play. Aside from private households, there is also significant potential to cut

231 | Salience describes the extent to which a product is visible or noticed, see Reisch/Sunstein 2021.

232 | See Bund Ökologische Lebensmittelwirtschaft 2021.

233 | See BMEL 2019a.

food waste in the out-of-home eating sector and through cooperation with food banks. In addition, it is important to strengthen the infrastructure for distributing surplus food.[234] At the industry level, trading standards could be amended to reduce the amount of food thrown away due to excessively stringent quality or labelling standards.[235] Other campaigns that can serve as a model include the recently concluded "Genießt uns!" (Enjoy us!) initiative, which gave awards to companies that introduced measures to tackle food waste across the value chain.[236] Further research is also needed to identify other effective food waste reduction measures and initiate their implementation.[237]

4.4.2 Product labelling and informed purchase decisions

It is already mandatory to provide information to consumers for some individual products such as eggs – in this instance, about how the hens were kept and the origin of the eggs. In most cases, however, information about products' environmental impacts can only be found indirectly. In the organic farming sector, this information is often provided by members of organic growers' associations, which establish and verify compliance with standards for crop cultivation, livestock farming and processing. Without spending inordinate amounts of time, it is difficult for consumers to gain an overview of the meaning and credibility of the plethora of different labels so that they can make informed purchase decisions. Moreover, the exact meaning of some of these labels can often be unclear. The introduction of a single, standard environmental impact label would thus significantly improve the information supplied to consumers by the retail trade.[238] This label would provide a summary of the environmental impacts of nitrogen, as well as other environmental factors relevant to crop cultivation, livestock farming and food production, such as greenhouse gas emissions and water consumption.[239, 240] To make an informed decision, consumers need data on the environmental footprint of producing particular products. It will also be necessary to decide on the relative weight that the label should attach to different issues such as biodiversity, climate protection and water consumption. An environmental impact label could be implemented as a reliable, independently certified private or public quality label.[241] The advantage of a government label is that consumers would likely trust it more. It would also create a level playing field for the many different types of information about products' environmental impacts. Origin labelling such as already exists for certain products could also be employed in this context.[242] Any government schemes would need to be checked for compliance with EU competition law to ensure that they did not discriminate against other member states or their produce.

General knowledge about how food is produced, how to prevent food waste and the environmental impacts of food production can be strengthened by addressing these topics through school and social education. Raising awareness about sustainable consumption is also an important part of the German Government's National Programme on Sustainable Consumption.[243] As mentioned above, the trend for consumers to choose more nitrogen-efficient and nutrient-efficient products is a welcome development in sustainable nitrogen use. Education initiatives could provide information about consuming plant-based and animal products, their health and environmental impacts, farming and animal welfare, and food labelling (including the meaning of labels under the EU Organic Production Regulation and of best-before dates as distinct from use-by or expiry dates).[244]

4.4.3 Nudging

In addition to demand-side instruments such as taxes, regulations, information and education, another consumer policy instrument currently being explored to promote sustainable purchase decisions is nudging.[245] Nudging can be used to

234 | See Deutsche Bundesregierung 2019.
235 | See BMEL 2012.
236 | See Tafel Deutschland e.V. 2014.
237 | See WBAE 2020.
238 | See ibid.
239 | See Deblitz et al. 2021.
240 | One example is the Eco-Score label, which is currently being trialled in some stores in Berlin.
241 | See BMU et al. 2019.
242 | See Spiller et al. 2021.
243 | See BMU et al. 2019.
244 | The EU Organic Production Regulation requires products labelled as organic to meet certain production standards. Communicating information about these standards can help consumers to make informed purchase decisions.
245 | See Reisch/Sunstein 2021.

encourage sustainable eating by making it easier for consumers to choose sustainable food products. Nudges are most effective if they are simple, attractive, socially relevant and well-timed.[246] Nudges for sustainable everyday eating include providing a wide selection of affordable vegetarian meals as standard in public canteens. Canteens can provide information about the environmental and health impacts of different foods and offer attractive alternatives. Another example of nudging involves the intuitive presentation of dietary recommendations in the form of an easy-to-understand plate graphic instead of a complex pyramid (simplification). Nudges target market actors' actual behaviour and can help to improve the effectiveness of other instruments such as regulation or information if these are failing to achieve the desired impact.[247]

Nudging seeks to encourage or facilitate a particular behaviour without resorting to bans, financial incentives or coercion.[248] Some critics fear that soft instruments like this could supplant other measures such as regulation, while others regard them as an unacceptable encroachment on individual freedom of choice.[249] Accordingly, if nudging is employed as a policy instrument, it is important to ensure that it is done transparently. People should also have the freedom to opt out and make other choices, and it should be used in addition to rather than instead of more effective policies.

Nudging measures should be accompanied by targeted information campaigns informing consumers about the scale and significance of the environmental impacts associated with the products they consume. Successful pilot projects[250] in the field of sustainable food production have found that consumers are fundamentally willing to make sustainable consumption choices if the impact of these choices is properly explained. Projects like this also help to strengthen communication between farmers and (better informed) consumers by showing consumers the direct positive impacts of their purchase decisions.

246 | See Reisch/Sunstein 2021.
247 | See ibid.
248 | See ibid.
249 | See WBAE 2020.
250 | E.g. the "Wasserschutzbrot" project, a groundwater protection initiative promoting bread made from wheat cultivated without recent nitrogen fertilisation.

5 Recommendations for sustainable nitrogen use

In this chapter, the basic options for promoting sustainable nitrogen use described in Chapter 4 are translated into a series of key recommendations. In the interest of keeping this overview as brief and to the point as possible, extensive references to Chapter 4 are avoided.

Nitrogen is an essential nutrient for plants and animals. While an adequate level of nitrogen inputs is necessary, excessive inputs can be extremely harmful to humans and the environment. Sustainable nitrogen use aims to resolve this conflict as effectively as possible. Nitrogen surpluses must be prevented to protect human health and the environment by preserving soil fertility, good water quality and biodiversity. Accordingly, nitrogen surpluses are a key indicator in the German government's sustainability strategy, which includes the target of reducing the nitrogen surplus from its current level of around 90 kilograms of nitrogen per hectare agricultural area to 70 kilograms by 2030. However, this target – which was set by policymakers – falls short of what is required to tackle the most pressing environmental problems. Even with a nitrogen surplus of 70 kilograms of nitrogen per hectare agricultural area, some 1.2 million metric tonnes of nitrogen will still remain in the environment every year, with all the impacts that this entails (see Chapter 3.1). The Agriculture Commission at the German Federal Environment Agency has called for a nitrogen surplus target of 50 kilograms of nitrogen per hectare agricultural area.[251, 252] However, neither of these recommended limits of 70 or 50 kilograms of nitrogen per hectare agricultural area is evidence-based. Consequently, these figures should be reviewed and replaced by a new target if necessary. The target should also reflect differences in site conditions, especially with regard to climate, soil and the ecological sensitivity of natural habitats, and could therefore vary from one region to another.

To achieve the goal of significantly reducing nitrogen surpluses, the recommendations in this acatech POSITION PAPER adopt a whole-system perspective that addresses the entire agricultural value chain (see Chapter 2). Agriculture's central role as the main emitter of nitrogen compounds in Germany is thus placed in a wider context that also recognises the significance of other actors. The resulting recommendations focus on the following four fields: creating sustainable management structures, reforming the economic and regulatory framework, developing knowledge management and sustainable technology, and promoting sustainable consumer behaviour (see Figure 10). It is vital to reflect variation in site conditions and local factors, for instance regarding the natural environment and its soils and climatic and topographical conditions. Differences in technological infrastructure and farm structures must also be considered. One key aspect of the recommendations outlined below is the chronological order in which they are addressed and how soon they will take effect. Changes to management structures or nitrogen pricing, for example, should be initiated as soon as possible, since their impact will take longer to be felt. On the other hand, knowledge management and technology development are continuous processes that can have both an immediate and a longer-term impact.

5.1 Sustainable management structures

5.1.1 Reduce regional concentration of livestock farming

The regional concentration of livestock farming is highly correlated with nitrogen surpluses (see Figure 7). The introduction of a general limit on livestock density throughout the agricultural sector, like the limit that currently exists for organic farms, is a highly effective policy option that should be implemented as a matter of priority. This measure would reduce the amount of farm manure in the relevant regions, addressing one of the reasons for their high nitrogen surpluses. At the same time, a more balanced regional distribution of livestock farming within Germany would enable better spatial coordination of arable and livestock farming nutrient cycles, allowing mineral fertilisers to be replaced by farm manure. Another advantage of this policy option is that environmental impacts and costs would be reduced as a result of shorter transport distances and lower outlays for manure storage.

251 | See UBA/BMU 2017.
252 | See UBA 2015b.

Published in 2016, the Climate Action Plan 2050[253] establishes a concrete, nationwide target of limiting stocking density to less than two livestock units per hectare. This regulation seeks to address the high stocking densities in the German regions where livestock farming is concentrated and nitrogen surpluses are high, and should be implemented as soon as possible. The introduction of a livestock-to-land ratio – as called for by various parties including the new German government that took office in 2021[254] – must also apply to existing facilities. It should be accompanied by appropriate measures to address grandfather clauses, e.g. financial assistance and transition periods. In addition, the upper limits on livestock densities should reflect site conditions and be set at a lower level in regions where this is appropriate. For instance, crops in locations with lower yield potential are able to take up less nitrogen, meaning that they utilise lower overall quantities of manure and mineral fertiliser than in other locations. Accordingly, livestock densities should be lower in regions where yield potential is generally lower. All Germany's federal states should base their regulations for building new animal housings on the appropriate livestock density for each region.

Lower livestock densities go hand in hand with improved animal welfare. If implemented, the animal welfare recommendations of the Animal Husbandry Competence Network (German: Kompetenznetzwerk Nutztierhaltung) will have a major impact on livestock farming.[255] Statutory regulations increasing the minimum area per animal could reduce the number of livestock kept in individual housings. In this way, animal welfare policy could help to reduce regional livestock concentration, provided that no or only a few new housings are built to compensate for the lower stocking density. Consequently, any major changes to animal husbandry regulations should not only consider the relevant environmental impacts in relation to nitrogen but should also take animal welfare and other environmental effects such as methane emissions into account.

5.1.2 Expand organic farming, make conventional farming more sustainable

Both fertilisation levels and farming intensity are generally very high in Germany. Nitrogen surpluses can be reduced with only a slight drop in yields by employing a mix of different farming systems tailored to site conditions, taking ecosystem interrelationships into consideration and making use of ecosystem services. In the medium term, diverse cultivation systems can also strengthen the agricultural sector's resilience to climate change impacts and help to maintain biodiversity and soil fertility. Conventional and organic farming can learn from each other, creating a farming system that is both sustainable and efficient.

Reducing nitrogen surpluses in conventional farming is an urgent challenge that is key to sustainable nitrogen use. It can be achieved by combining various different approaches. Coupled with a reduction in the use of mineral fertilisers, diversified crop rotation including legumes and catch crops – as practised by organic farmers – is a promising means of reducing the nitrogen surplus in conventional agriculture.[256] It will also be necessary to require the use of appropriate general practices such as precision fertilisation based on nitrogen balance accounting (see next section). In addition, manure storage and application and tillage will need to be optimised.

Increasing the amount of land devoted to organic farming is another measure that can help to reduce nitrogen surpluses. Organic farms have significantly lower nitrogen surpluses and are often more nitrogen-efficient than comparable conventional farms. Another advantage of this policy option is that its implementation would not entail extensive, costly administrative and regulatory measures over and above those regulations that already exist. In view of the growing demand for sustainably produced food, there is currently a strong case for the further expansion of organic farming in Germany and throughout the EU. However, the impacts of increasing the proportion of organically farmed land should be scientifically researched and reviewed. A report on the impacts could be drawn up once an expansion target (e.g. 20% of all agricultural area) had been achieved.[257] This is important, since, depending on the context and product,

253 | See BMU 2016.
254 | See SPD/Bündnis 90/Die Grünen/FDP 2021.
255 | See Kompetenznetzwerk Nutztierhaltung 2020.
256 | Sometimes referred to as hybrid farming, see e.g. BMEL 2020b.
257 | See WBAE 2020.

organic farming produces lower yields – substantially lower in the case of cereal crops, for example. This can significantly affect organic farming's sustainability in terms of its land use or greenhouse gas emissions to yield ratio. Closing the yield gap between organic and conventional farming is a challenge that must be urgently addressed by organic farming research and development. A stronger focus on breeding research will be especially important and should encompass new methods that have not previously been permitted on organic farms. It will also be vital to investigate ways of improving soil fertility and organic plant protection methods.[258, 259]

5.2 Economic and regulatory framework

5.2.1 Promoting efficient nitrogen use through pricing

One possible policy option would be to internalise the external costs to society of nitrogen inputs into the environment. The main goal of such a policy would be to make lower nitrogen surpluses economically attractive to farmers. The two financial instruments outlined below – a nitrogen surplus levy and a transaction tax on mineral fertilisers and animal feed – can both be used to internalise external costs. Regardless of whether nitrogen pricing is introduced in the form of a nitrogen surplus levy or a tax on the purchase of mineral fertilisers and bought-in feed, it will be up to farms to decide which measures they take to improve nitrogen use efficiency in keeping with their own specific circumstances. The introduction of pricing could be aligned with and supported by existing regulatory measures. The detail of the pricing system would need to address its impact on competitiveness and the effects of major fluctuations in the market price of agricultural inputs.

A nitrogen surplus levy calculated on the basis of a farm's nitrogen balance budget is a more targeted means of reducing nitrogen surpluses than a tax on mineral fertilisers and bought-in animal feed, and can also reflect site conditions in different regions. On the other hand, it would involve relatively high administrative and auditing requirements, although these already exist for larger farms under the Nitrogen Balance Budget Ordinance and have applied even more widely from January 2023.[260] A nitrogen surplus levy should apply to the vast majority of farms, although exemptions could exist for very small operations that do not buy manure from other farms. The levy could also get progressively higher for each additional kilogram of surplus nitrogen, thereby creating a stronger economic incentive for farms with higher nitrogen surpluses.

An additional tax on the purchase of mineral fertilisers could also help to reduce nitrogen surpluses (see Chapter 4.2.1). A purchase tax would be relatively easy to implement and manage from an administrative perspective, since mineral fertilisers are only marketed by a handful of companies. It would have to be accompanied by a tax on bought-in animal feed aimed at reducing nitrogen surpluses caused by the nitrogen compounds in feed. While a tax like this targets the "bottlenecks" (importers and agricultural wholesalers), it would also have to apply to direct sales between farms unless the manure is returned to the farm that produced the feed. Despite the higher administrative burden, it should still be feasible to implement such a tax. However, there are other problems with this policy option: a tax would not reflect regional differences and would increase the price of fertilisers in general rather than directly targeting the nitrogen surplus. At a time when fertiliser and feed prices are already high, these drawbacks mean that a tax would probably be less effective than a nitrogen surplus levy.

The revenue from a nitrogen surplus levy could be distributed as a rebate to all farms, for example based on the area of farmed land. The same approach could be used for the revenue from a purchase tax, provided that it could be ring-fenced without contravening the relevant law. Alternatively, instead of giving farmers a rebate, the revenue from pricing could be used to fund measures to promote sustainable nitrogen use in Germany.

258 | See Hamm et al. 2017.
259 | See Haller et al. 2020.
260 | In order to ensure effective implementation of a nitrogen surplus levy, the exact nature and extent of the auditing mechanisms would need to be carefully defined.

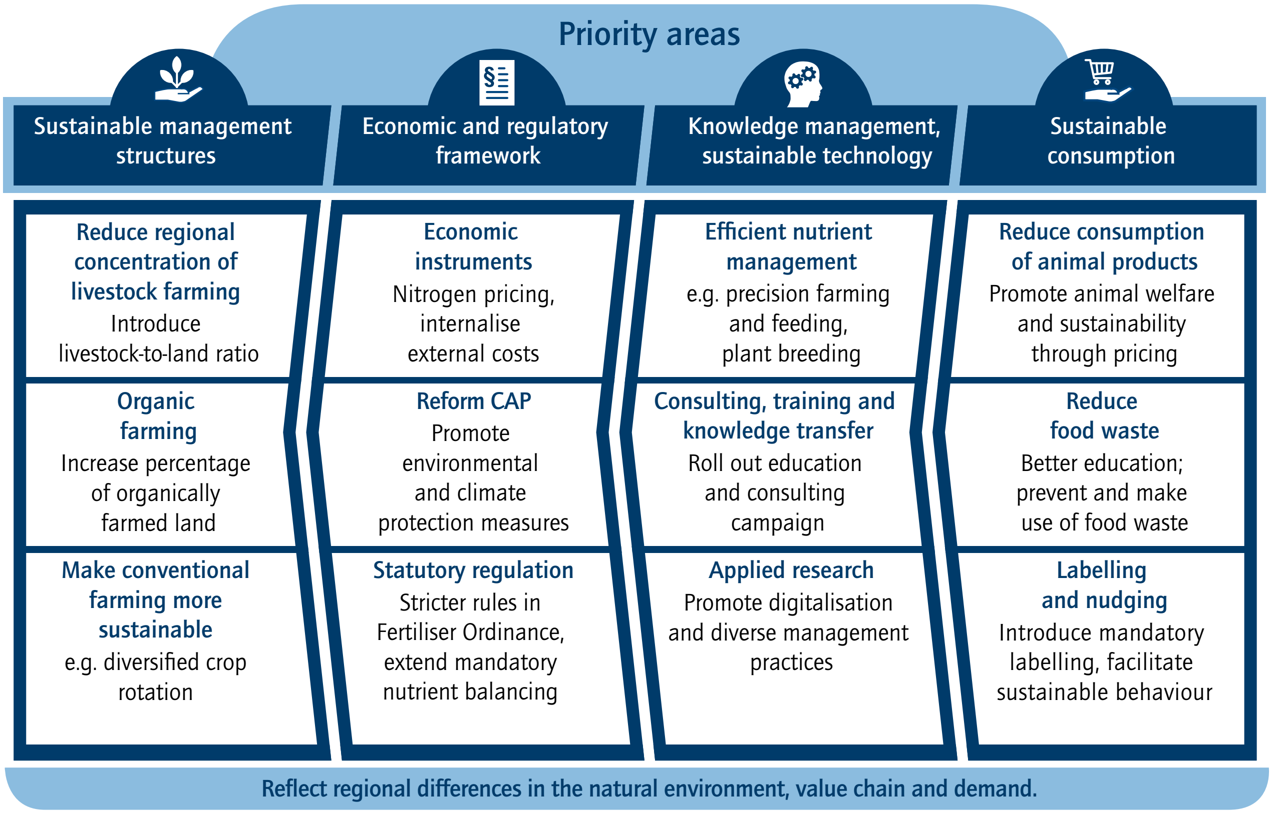

Figure 10: Priority areas for sustainable nitrogen use (Source: authors' own illustration)

5.2.2 Tax animal products

The Animal Husbandry Competence Network proposes increasing V.A.T. on animal products or introducing a quantity-based consumption tax, supported by social policy measures.[261] While this proposal is aimed at reducing consumption of animal products, it also promotes sustainable nitrogen use in farming by indirectly lowering agricultural nitrogen inputs into the environment. An increase in the V.A.T. rate would be relatively easy to implement from an administrative perspective. Moreover, a quantity-based consumption tax would need to be checked for compliance with EU state aid law. Despite this reservation, there is no doubt that, if supported by social policy measures, this policy option would influence consumer behaviour and should therefore be welcomed.

Higher sustainability and animal welfare standards in Germany could result in the relocation of some agricultural production to other countries. This could lead to loss of income for farmers and drive up imports from countries with potentially lower production standards. It will thus be important to coordinate measures across the EU and with third countries or associations of states, insofar as this is politically feasible. If Germany succeeds in implementing effective national measures, it will also be able to lead the way on sustainability, environmental protection and animal welfare within the EU.

261 | See Kompetenznetzwerk Nutztierhaltung 2020.

5.2.3 Reform the Common Agricultural Policy, focusing financial support on environmental and climate protection measures

According to a decision of the German cabinet, 25% of future direct payments under the Common Agricultural Policy (CAP) will have to be linked to environmental and climate protection measures.[262] Conventional farms can choose from a range of such measures. Cultivation of diverse catch crops including legumes, land set aside and grassland extensification are among the measures that can help to reduce nitrogen inputs into the environment.

At national level, the reallocation of additional funds from the first to the second pillar of the Common Agricultural Policy is one policy option that could be implemented rapidly and would serve to promote more nitrogen-efficient organic farming, conversion of livestock housing and other environmental measures in the agricultural sector. From 2023, 10% of funds are due to be reallocated from the first to the second CAP pillar, gradually rising to 15% by 2026.[263] However, an even larger proportion of the funds should be reallocated, and this also needs to happen faster than currently planned. The federal states decide which measures are funded with this money and the level of funding allocated to each measure. It is important to ensure that, alongside other goals, the chosen measures and the funding made available to them focus on supporting sustainable nitrogen use in agriculture.

Linking direct payments under the current Common Agricultural Policy to environmental and climate protection measures only has a limited impact on the reduction of nitrogen inputs into the environment, not least because most of the measures are voluntary and are not explicitly aimed at reducing the nitrogen surplus. However, even if payments for environmental and climate protection measures only achieve a modest reduction in nitrogen inputs into the environment, they should still largely replace the CAP's area-based direct payments, since doing so will also help to address agriculture's many other environmental impacts.

5.2.4 Stricter rules in the Fertiliser Ordinance, extend mandatory nitrogen balance accounting

The rules governing nitrogen balance accounting in farms are set out in the Nitrogen Balance Budget Ordinance (German: Stoffstrombilanzverordnung – StoffBilV). The current version of this ordinance suffers from significant weaknesses and is in some places even less effective than the 2017 version of the Fertiliser Ordinance (German: Düngeverordnung – DüV) (see Chapter 4.2.2). Although the Nitrogen Balance Budget Ordinance's scope was extended from the beginning of 2023, the current plans fall short of what is required. To achieve widespread sustainable nutrient management, the ordinance must apply to almost every farm, with exemptions for very small operations that do not buy in manure or digestate from other farms. Furthermore, the nitrogen surpluses permitted by the current version of the ordinance are too high. The targets in the Nitrogen Balance Budget Ordinance should be regularly reviewed and updated based on expert advice. The 2020 amendment to the Fertiliser Ordinance has come into force, including the "red zones" designated for the first time in 2021 and other measures specific to individual federal states. It is thus particularly important to determine whether the nitrogen surplus target of 70 kilograms per hectare per year included in the German government's sustainability strategy is achievable and whether there are evidence-based grounds to set a lower target. The Nitrogen Balance Budget Ordinance also lacks effective mechanisms for sanctioning farms that exceed the upper limit. Supporting a nitrogen surplus levy with meaningful sanctions is key to ensuring that this instrument is effective in practice. If this is done, nitrogen balance accounting can become one of the main drivers of sustainable, efficient nitrogen use, providing valuable support for other structural and economic measures.

The Fertiliser Ordinance and its rules on the application of farm manure have been amended several times in recent years. The use of broadcasting on tilled farmland has been banned since 2020 and the ban will be extended to pasture from 2025. Also from 2025, farm manure applied to untilled arable land will have to be incorporated within one hour of spreading. Despite these changes, there is still room for improvement. For example, broadcasting of farm manure should also be banned on untilled farmland. It is also technically possible to further reduce

262 | See BMEL 2021a.
263 | See ibid.

ammonia emissions by incorporating manure into the soil immediately after spreading. The addition of inhibitors helps to reduce nitrogen inputs into the environment by slowing down the rate at which the fertiliser is released. The existing rules governing the use of urease inhibitors and the incorporation of urea fertiliser should be amended so that they also apply to the use of fertiliser mixes with less than 44% urea/nitrogen.[264]

With the exception of the designation of nitrate-contaminated and eutrophicated areas under Section 13a of the Fertiliser Ordinance, specific local soil, geological and climatic conditions are not currently taken into account by either the Fertiliser Ordinance or the Nitrogen Balance Budget Ordinance. The local environmental impact of nitrogen surpluses depends on the conservation status and vulnerability of local aquatic and terrestrial ecosystems and protected biotopes and species. Critical levels or loads can be calculated and designated for every part of the country in order to ensure that these regional and local ecosystem protection requirements are fully reflected. The protection of natural ecosystems, including those in nature reserves, will also require a reduction in airborne ammonia emissions, especially from livestock farming (see Chapter 5.1).

5.3 Knowledge management and sustainable technology use

5.3.1 Promote efficient, digital nutrient management

In conjunction with data management systems and computer modelling, modern agriculture and sensor technology is able to adjust for local differences in high resolution, even within individual fields. The tailoring of tillage and of fertiliser and plant protection product application to specific subplots (precision farming) will play a vital role in reducing nitrogen emissions in years to come. The growing automation of agriculture is lowering farmers' workloads, potentially freeing them up to reduce nitrogen inputs into the environment by carrying out multiple light fertiliser applications.

Precision feeding follows a similar approach to precision agriculture. Low-nitrogen, needs-based livestock feeding is an important means of improving nutrient management, thereby helping to reduce nitrogen surpluses and ammonia emissions. Moreover, the benefits are not confined to regions with high quantities of liquid manure.

Nitrification inhibitors are another option for sustainably reducing nitrous oxide emissions. The overall environmental impact of nitrification inhibitors is fundamentally positive, provided that the total level of nitrogen in the fertiliser is reduced and enrichment in the environment is prevented. Nitrification inhibitors could, for example, be added to the list of options eligible for Common Agricultural Policy eco scheme funding.

In order to accelerate widespread access to costly low-emission agricultural technology, regulations on the use of particular technologies could be supported by financial assistance. The "farmer's billion" funding programme offers subsidies for the acquisition of agricultural technology and, if continued in a similar form, could help to mitigate the high investment costs for farmers. The deployment of this technology will require the establishment of the necessary basic infrastructure, especially high-speed Internet access in rural areas. The adoption of a common approach to data management by all the federal states would be extremely helpful and desirable in this context.

5.3.2 Support consulting and training initiatives and knowledge transfer

Sustainable nitrogen use in agriculture is a complex topic involving multiple systemic interactions, for example between fertilisation, tillage, crop rotation and plant protection, as well as overarching sustainability and economic factors. Each individual farm must therefore develop its own efficient management and fertilisation strategy for preventing nitrogen surpluses. Farms should have access to reliable information so they can choose the right solution for their needs from the multitude of available options, including information about how to use modern agricultural technology and about the latest research findings. Agricultural consulting services and training and professional development all play an important role in this context by collating and communicating the available knowledge and facilitating access to it locally.

Consulting services should always be independent and provided by consultants with no personal financial stake. This will call for much greater support from the federal states, i.e. adequate

264 | See LfL 2021c.

funding and promotion of the official government consulting service, which is no longer provided in some federal states and is extremely limited in others. The revenue from nitrogen pricing could be used for this purpose (see Chapter 5.2). Certification of private sector consulting services would ensure that they covered all the relevant aspects of sustainable farming.

Organic farming principles, the full spectrum of organic farming methods and the opportunities associated with Agriculture 4.0 should be better integrated into training and professional development provision at every level, be it agricultural colleges, vocational colleges or universities. The relevant professional associations and bodies should review curriculums with this in mind and update them as necessary. Nutrient efficiency should also form an integral part of courses at every level of training and professional development.

5.3.3 Strengthen research into sustainable farming

Sustainable and efficient nitrogen use in farming requires a knowledge of how to use sustainable management methods and techniques correctly and of their ecological and economic benefits.[265] To ensure that research findings are implemented in practice as soon as possible, pilot projects and demonstration farms can help to promote more widespread adoption of the relevant techniques while at the same time capturing data for researchers. A research network including working farms would offer benefits for both researchers and farmers.

In view of the environmental changes occurring as a result of climate change, further advances in nitrogen-efficient management structures and farming technology will be another important enabler of sustainable nitrogen use in the long term. This should include optimisation of sensor-based fertilisation technology, fertilisation algorithms and digital fertilisation systems that enable precision fertilisation. Soil science research into the role of local variation and the biological conversion of soil nitrogen compounds is also key to sustainable nitrogen use. Long-term trials combined with nationwide monitoring can deliver particularly valuable data.

Breeding stress-tolerant or nitrogen-efficient plants that are more resistant to heat and drought or more efficient at taking up and utilising nitrogen is a key research area for sustainable nitrogen use and for agriculture in general. Plants bred with the relevant traits can reduce crop losses and utilise lower levels of soil nitrogen more efficiently. Weather-related failure of crops that have already been fertilised contributes to nitrogen inputs into the environment, since the plants are no longer able to take up the applied nitrogen.

There is also a need for process and product innovations for the production of protein foods that can partly replace meat production and thus reduce the associated nitrogen inputs into the environment. Plant-based products are a particularly promising option for which there is growing consumer demand. Protein can also be produced using processes with closed nutrient cycles. However, it remains doubtful whether these power-hungry processes can contribute to a sustainable food supply, at least for the time being.

5.4 Sustainable consumption and informed purchase decisions

5.4.1 Reduce consumption of animal products and food waste

Food production has multiple environmental impacts, of which nitrogen inputs are just one. An increase in the consumption of sustainably produced foods will indirectly reduce nitrogen inputs into the environment. Reduced consumption of animal products has numerous benefits[266] in terms of climate protection, animal welfare and human health.[267] It can thus be justified on different grounds at the same time through motive alliances,[268] with specific communication being targeted at different groups. As well as higher end-consumer prices for animal products (see Chapter 5.2), the provision of widely accessible information can also encourage consumers to change their diets.

265 | See acatech 2020.

266 | See WBAE 2020.

267 | In 2019, annual meat consumption in Germany stood at around 57 kilograms per person. This is almost double the maximum of 16–31 kilograms per person recommended by the German Nutrition Society, see Deutsche Gesellschaft für Ernährung e.V. 2021; BLE 2020a.

268 | The term "motive alliances" describes different motives and combinations of motives for the same dietary choices and consumer behaviours, see Brunner 2009.

Preventing food waste is another important means of reducing agriculture's environmental impacts. It is also necessary to strengthen the infrastructure for distributing surplus food. At the industry level, trading standards could be amended to reduce the amount of food waste (see Chapter 4.4). As far as possible, the aim should be to create a circular food economy. In view of the German government's target of halving food waste in the retail and consumer sectors by 2030,[269] more research is needed to identify and implement further effective measures in this area.

5.4.2 Introduce product labelling and make use of nudging

Food labelling helps to inform consumers and provide transparency regarding the sustainability of different products and production methods.[270] Labelling can also influence the retail trade by providing valuable guidance for the active selection and marketing of its product range. Product labels that inform consumers about the nitrogen inputs into the environment associated with the production of a particular product can influence their purchase decisions and thus ultimately the way the products are produced. However, in order to prevent the emergence of a plethora of different labels and measures in the consumer sector, the optimal solution would be to introduce a single, trusted, private or public environmental impact label that provides information on nitrogen inputs and other key environmental impacts, such as a product's carbon or water footprint. This will call for the creation of a database with the relevant information and a consensus on the weighting of the different factors. The clear advantage of a government label is that it would be standardised and highly trusted by consumers. In addition, it will be important to improve people's knowledge about sustainable eating and how to prevent food waste by addressing these topics more thoroughly in school and social education.

Nudging can also raise consumer awareness of the environmental impacts of different foods. Nudging is an instrument that aims to make it easier for consumers to choose healthier, more sustainable alternatives by encouraging certain behaviours. It is vital to ensure that nudging is used transparently to prevent criticism that consumers are being manipulated or denied freedom of choice. Nudging measures should also be accompanied by targeted information campaigns (see Chapter 4.4).

Communal catering facilities offer an excellent opportunity to provide healthy, sustainably produced food and inform the public about the environmental and health impacts of different products. For instance, they can offer locally produced organic foods and promote plant-based alternatives to meat. The state can set an example by making the relevant adjustments to the procurement rules for public catering facilities. Since the impact of these measures filters through to every part of the agricultural value chain, they can make a significant, direct contribution to sustainable nitrogen use in agriculture.

269 | See BMEL 2019a.
270 | See WBAE 2020.

Appendix

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What form should agriculture in Germany take in the future? Scientists, policymakers and the general public are currently discussing this question intensively. Sustainable nitrogen use is an important part of this discussion, though it has received little public attention so far. Agriculture adds approximately 1.5 million metric tonnes of reactive nitrogen to the environment in Germany every year. Nitrogen in the form of various compounds is a significant contributor to climate change, biodiversity loss and soil, air and water pollution. As a result, nitrogen inputs from agriculture into the environment are estimated to incur societal costs between €30 billion and €70 billion a year.

These problems have been known for decades, and extensive research has been performed in this area. However, measures implemented to date have not been effective, as indicated by the slow decline of nitrogen inputs from agriculture. This acatech POSTION PAPER considers the entire value chain, from agricultural production right up to the end consumer. This provides the basis for a series of recommendations geared towards more efficient and sustainable resource utilisation and a reduction of nitrogen inputs into the environment.