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REVERSING THE NITROGEN CRISIS

ROLE OF PLANT-BASED DIETS AND SUSTAINABLE FARMING

alpro foundation
knowledge in plant-based nutrition

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CONTENT

KEY POINTS

- **Human activities have increased the levels of reactive nitrogen (Nr)** in our environment, with detrimental effects on **biodiversity, climate, water quality, air pollution, ... and human health.**
- The biggest contributor to this surplus in Nr is the **agriculture** needed to support our current dietary habits, which are highly focused on animal protein.
- There are two ways we, as individuals, can positively impact (reduce) the Nr levels in our environment: (1) through our **food choices** (choosing plant protein over animal protein) and (2) through reducing **food waste** (both discarded food and overconsumption).
- Such a transition would not only help reduce Nr levels, but would also benefit our **health and reduce climate change and biodiversity loss.**
- Other solutions should be implemented mainly at the governmental level to **support sustainable agriculture and food production** (improve N use efficiency [NUE]).

INTRODUCTION

With climate change now firmly on the political agenda of many countries, the Netherlands is adding another issue to its agenda: the nitrogen (N) crisis. While reactive nitrogen (Nr) is naturally present at low levels and essential to life, human activities have caused a surplus in Nr, negatively impacting water quality, air quality, soil degradation, climate change, stratospheric ozone and causing significant loss of biodiversity (e.g. Galloway et al., 2003; 2008; Erisman et al., 2013).

The Netherlands is the first country to have the N crisis on the political agenda, but more countries will follow since all European countries are subject to the judgement of the European Court, which states that the quality of the Natura 2000 areas should be conserved and therefore N pollution reduced. This report will use the Netherlands as an example to highlight the N crisis. Where relevant, a bridge to the European context will be made.

While the Dutch domestic sources such as traffic (22%), households (5%), industry (5%) and the energy sector (0.9%) all contribute to the Nr deposition, the biggest contributor is agriculture (66%). The type of agriculture needed to sustain our current dietary habits – which are rich in animal protein – has a large N footprint. Deposition of Nr to natural areas is the main cause of the N crisis in the Netherlands.

Agriculture, traffic, and industry (facilities burning fossil fuels) have overall reduced their emissions since 1990 by 60%. Nitrogen oxides (NO_x) emissions from traffic and the energy sector have further declined significantly since 2000, and those from industry are at low levels, whereas N emissions from agriculture have remained stable for the past decade. While efforts were made towards low emission animal housing systems, these efforts cannot counteract the growing demand for animal protein.

This raises an important question. Can a shift in our food consumption patterns help reverse the increasing trend of Nr?

THE TWO FACES OF N

N is abundantly available, with approximately 78% of the atmosphere being N_2 (molecules consisting of 2 N atoms, which are strongly bound to one another; Fig. 1). Atmospheric N_2 is odourless, harmless, and unavailable for metabolic processes. In the natural N cycle, atmospheric N_2 is turned into Nr (compounds such as ammonia (NH_3) and NO_x). Nitrogen in its reactive form is essential for life: it is present in amino acids, DNA and RNA, and it plays a role in photosynthesis and many other biological processes that are essential for life on Earth.

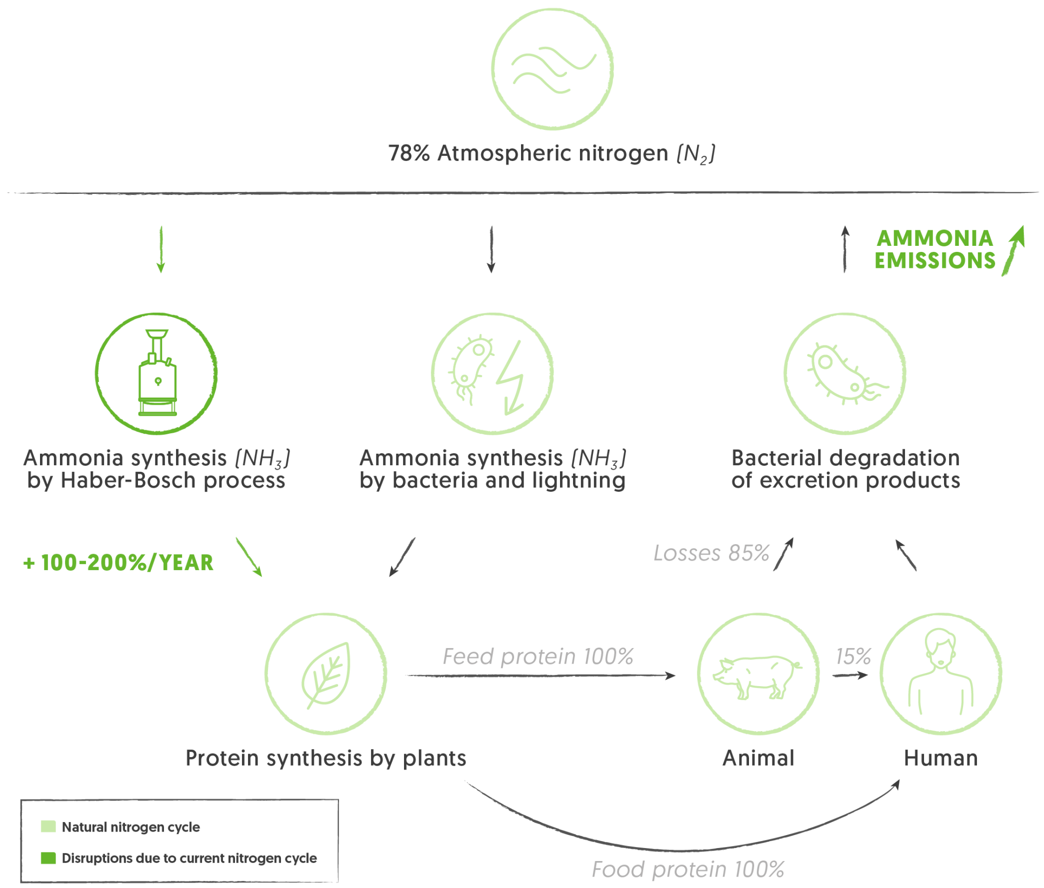

FIGURE 1. THE SIMPLIFIED N CYCLE, FOCUSSING ON AMMONIA, WHICH EXCEEDS NO_X FROM FUEL COMBUSTION.

Both the NH_3 input (via N fertilizers) and the output (emissions mainly stem from degradation of livestock manure, because human excretion products are generally fully degraded in sewage treatment plants) have been accelerated by man. Compared to the natural cycle (until about 100 years ago; light green), we have currently added over 100% of Nr (dark green).

Abbreviations: N, nitrogen; NH_3, ammonia; NO_X, nitrogen oxides; Nr, reactive nitrogen.
Adapted from: Personal collection Harry Aiking.

Some of these natural processes that create Nr include volcanic eruptions, thunderstorms, forest fires and biological N fixation (Fig. 2). The latter is quantitatively more important, and brought about by certain bacteria, which are living in symbiosis with plants, such as legumes. **All these produce only small amounts of Nr and our ecosystems have evolved various ways to optimally use this limited supply.**

In the early 1900s, however, human activity has also started to produce Nr in the form of N fertilizers, which are increasingly released into the environment. This has significantly disrupted the natural N cycle.

FIGURE 2. NATURAL SOURCES OF Nr (clockwise): volcanic eruptions, lightning, Nitrobacter (N fixating bacteria) in root nodules and forest fires. These only produce small amounts of Nr, which our ecosystems can optimally use.

AN INTERNATIONAL PROBLEM

Resulting from a globally increasing population, a rapid increase in per-capita consumption and a concomitant depletion of resources, human pressure on the Earth has reached a point where environmental change is global and, in many respects, irreversible. Yet, some essential changes might still be able to turn the tide.

Since not all of the Nr we produce deposits in the immediate surroundings, international actions and/or policies are needed to address this N crisis. Of the total NH_3 emissions produced in the Netherlands, only half is deposited locally. The rest is transported to other countries. Conversely, about 30-40% of the Nr in the Netherlands comes from abroad.

AGRICULTURE AS ONE OF THE MAIN CAUSES OF SURPLUS Nr

The amount of Nr produced by human activities is steadily increasing, and already exceeding Nr produced by natural processes. Galloway et al. (2021) estimate that globally in 2020, the total human global Nr creation rate (emission) was 226 Tg N/year (47% Haber Bosch fertilizer [HBF], 19% Haber Bosch industrial [HBI], 19% cultivation-induced biological N fixation [CBNF], 15% fossil fuel combustion [FF]). In contrast, the natural terrestrial biological N fixation rate was ~58 Tg N/year, or, 3- to 4-fold less than anthropogenic creation (Townsend and Howarth, 2010; Fowler et al., 2013; Galloway et al., 2021).

For a long time, there was enough naturally occurring Nr to feed the world's population (sufficient Nr to grow crops and provide the food needed for the small world population). As our population grew, these levels became insufficient. About 100 years ago it became possible to convert N_2 into ammonia on a large enough scale to sustain the population, in a way that is economically feasible and energetically efficient (Erisman et al., 2008; Smil, 2001). Agricultural practices increasingly depend on the use of chemical fertilizers to restore nutrients to the soil, thereby enabling farmers to produce higher food yields without the need for rotational cropping. It is estimated that currently more than 50% of the population is fed thanks to fertilizers (Fig. 3; Smil, 2001; Stewart, 2005; Erisman et al., 2008).

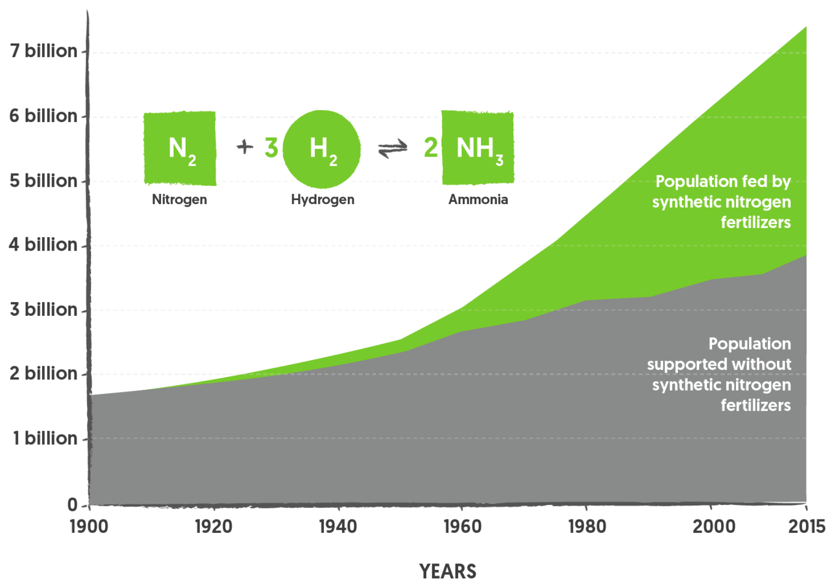

FIGURE 3. POPULATION SUPPORTED BY NATURAL Nr AND SYNTHETIC FERTILIZER.

With an increasing global population, naturally occurring Nr is no longer sufficient to feed everyone. Upon the discovery of a mechanism to convert N_2 into ammonia on a large scale, the number of people fed by synthetic N fertilizers increased significantly. Currently, more than 50% of the population is fed thanks to synthetic N fertilizers.

Abbreviations: N, nitrogen; Nr, reactive nitrogen. *Adapted from: Erisman et al., 2008.* https://ourworldindata.org/how-many-people-does-synthetic-fertilizer-feed/. *Accessed 23 April 2021.*

An unintended consequence of the availability of cheap and nearly unlimited N fertilizer is that the efficiency of its use has greatly diminished. Whereas natural processes have evolved to use N efficiently, crop production is highly inefficient in its N use. This inefficiency became even more pronounced with the specialization of agriculture, i.e. decoupling the production of plant-based and animal-based products and using the manure for crop production.

In addition, the production of N fertilizer requires a tremendous amount of energy. Single-handedly, this Haber-Bosch process accounts for > 1% of all annual energy production worldwide. Therefore, the anthropogenic acceleration of the N cycle is a main driver of climate change, in addition to a main driver of biodiversity loss (Aiking, 2014).

While NO_x emissions from traffic and the energy sector have declined significantly since 2000, and those from industry are at low levels, N emissions from agriculture have remained stable in Europe for the past decade (Fig. 4). Efforts to develop low emission animal housing systems and air scrubbers (decreasing the amount of Nr in the air) could not counteract the impact of more animals in larger housing systems.

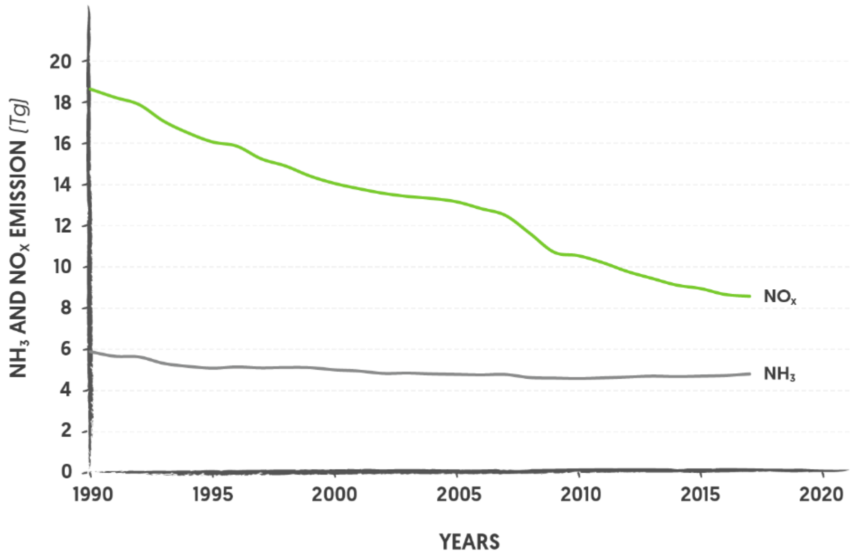

FIGURE 4. TOTAL EMISSIONS OF NH_3 (FROM AGRICULTURE) AND NO_x (FROM TRAFFIC, INDUSTRY AND THE ENERGY SECTOR) IN TERAGRAM (Tg)/YEAR FOR EEA-33.

NO_x emissions from traffic, industry and the energy sector have declined significantly since 1990, though NH_3 emissions from agriculture have remained stable during the last few decades.

Abbreviations: NH_3, ammonia; NO_x, nitrogen oxides. *Adapted from: EEA 2021.*

EFFECTS OF Nr IN THE ENVIRONMENT

The negative consequences of this human-generated change are becoming ever more apparent. Nr produced by human activities is largely lost to the environment. It transfers to soil, water and air, spreading to ecosystems where Nr levels have naturally been low. Numerous, often interlinked, thresholds for human and ecosystem health have been exceeded due to excess Nr pollution, including thresholds for drinking water quality (due to toxic levels of nitrates) and air quality (smog, particulate matter, ground-level ozone). But it does not stop there. Eutrophication of freshwater and coastal ecosystems (dead zones), soil degradation, climate change, and stratospheric ozone depletion are also well-established consequences of the man-modified N cycle (e.g. Galloway et al., 2003; 2008; Erisman et al., 2013; Bobbink et al., 2010).

Nr is also a significant driver of biodiversity loss. Regions with a high concentration of roads, industry and livestock farms, have intense Nr losses to the air. Consequently, they suffer tremendous terrestrial biodiversity loss.

Firstly, many terrestrial ecosystems are ill-equipped to handle the nutrient overload caused by ammonia deposition. When Nr is transported by air and precipitates, it enriches the soil and acts as a growth accelerator. Faster-growing species that can rapidly assimilate Nr and acid-tolerant species are favoured. Rare plants that need little Nr, such as orchids, herbs or heather disappear, because they are overgrown by plants that grow fast because of Nr, such as brambles, grasses or nettles. Next to that, the excess of Nr also significantly drives acidification of the soil and eutrophication. As valuable regions are losing both plant species and habitats at an accelerated rate as a result, this can also affect biodiversity of insects or other animals dependent on those plants and habitats, and reduce ecosystem resilience in the end. Fragile ecosystems and animals living on rare plants are threatened and disappearing.

Secondly, aquatic ecosystems react to Nr overload with algal blooms. Subsequent degradation of algal biomass by bacteria depletes all the oxygen in the water, with catastrophic impacts on fish and shellfish. For example, the Gulf of Mexico dead zone has a surface area that is half the size of the Netherlands, and in the Baltic Sea the dead zone is even bigger.

Some regions are hit harder than others by the deposition of Nr (Fig. 5). Europe is among the areas which are highly affected, causing biodiversity loss despite the efforts of the Natura 2000 network to protect its valuable areas (see chapter “Lifting the threat on protected natural areas”).

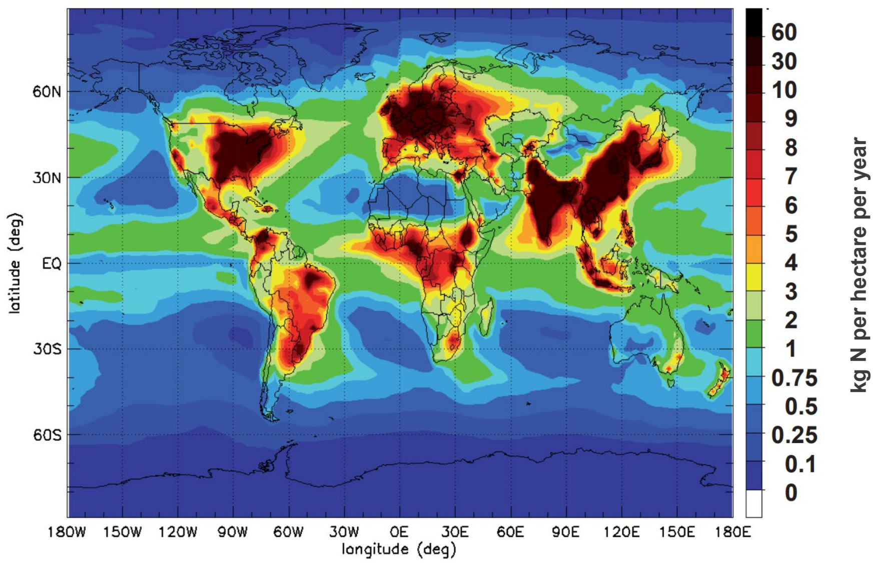

FIGURE 5. MODELLED ATMOSPHERIC Nr DEPOSITION.

Highly affected areas of biodiversity loss induced by excess of Nr deposition include central and western Europe, southern Asia and the eastern US, as well as parts of Africa and South America.

Abbreviations: deg, degrees; N, nitrogen; Nr, reactive nitrogen. *Source: Sutton et al., 2013.*

HOW CAN INDIVIDUALS MAKE A POSITIVE CHANGE?

As it has become clear that we are facing a serious Nr threat, the following question needs to be asked: How can we reduce these mounting impacts? Primarily, the nitrogen and carbon cycles need to be decelerated urgently, and in tandem. The focus should be on limiting the production of Nr and on increasing the Nr use efficiency. The next sections will detail the most important options: changing dietary habits, food waste, and agricultural production systems, as well as implementing certain technological options.

DAILY DIETARY CHOICES

The root of the problem in the Netherlands and similar urbanized countries is that there is too much new Nr produced domestically and entering from other countries. This includes imports of animal feed concentrates, fertilizers, as well as emissions from fossil fuel combustion. If we phased all of those out, there would be no Nr problem (and far fewer other environmental problems as well). However, giving up cars, meat and spacious living is not something done easily. Perhaps there might still be changes that are worth making to help save our climate and nature.

Disregarding the water content, the human body contains about 48% carbon, 30% oxygen, 8% N, 4% hydrogen [Frieden, 1972]. N is the third most abundant chemical element in our body, because it is a constituent of many biochemical compounds, notably DNA. Nutritionally, we derive N almost exclusively from protein. Therefore, Dutch adults require 50-60 g/d of protein [Health Council of the Netherlands, 2001], but on average they consume 170% of the required amounts [van Dooren and Seves, 2019].

It is well-known that, in parallel with increasing incomes, a dietary transition takes place from plant to animal food sources [Grigg, 1995]. For example, between 1950-2000 the **global population approximately doubled from 2.7 to 6 billion, but meat production increased fivefold** from 45 to 229 billion kg [Steinfeld et al., 2006]. Animals are increasingly held in concentrated animal feeding operations as intensive livestock farming, using increasing amounts of feed crops, such as soy and maize. Economically, that may be feasible, but **on average 6 kg of plant protein is required to produce 1 kg of animal protein, which increases the pressure on the environment** [Smil, 2000; Smil, 2001]. Consequently, merely 10-17% of fertilizer N ended up in human mouths to perform its vital functions in the body [Erisman et al., 2018], and the global N use efficiency keeps dropping. The choice of type of meat consumption has a large influence on the N efficiency [Fig. 6]. For example, consuming legumes directly, rather than feeding them to livestock first and then eating animal products, would improve the N use efficiency tremendously.

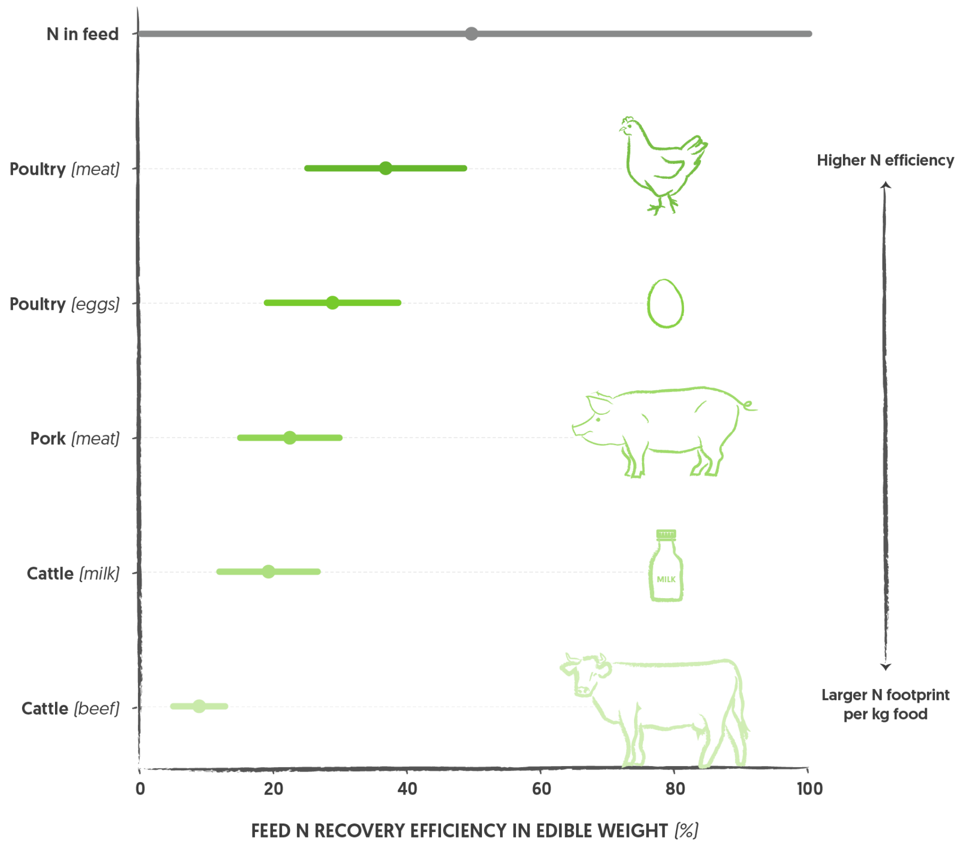

FIGURE 6. FEED N RECOVERY EFFICIENCY FOR VARIOUS TYPES OF ANIMAL PRODUCTS.

Animal products have a low N efficiency. Only roughly 5% to 50% of the N present in animal feed, is still present in its edible product.

Abbreviations: N, nitrogen. *Adapted from: Sutton et al., 2011.*

In the Netherlands, the animal to plant protein ratio in diets increased from 58:42 in 1961 to over 68:32 today (10% increase in animal protein; van Dooren and Seves, 2019). The changes across the EU-28 (European Union: 28 countries) seem even more extreme, from 44:56 in 1961 to 57:43 in 2019 (Fig. 7, 13% increase in animal protein). However, the Dutch diet historically contained the least plant protein in the EU-28, and the most animal protein. This can be traced back to its high proportion of cheese and dairy (de Boer et al., 2006; de Boer and Aiking, 2018). To reduce the current environmental impacts, many Dutch agencies (including the Health Council of the Netherlands) advocate a "reverse" protein transition, back to 50:50 by 2025-2030.

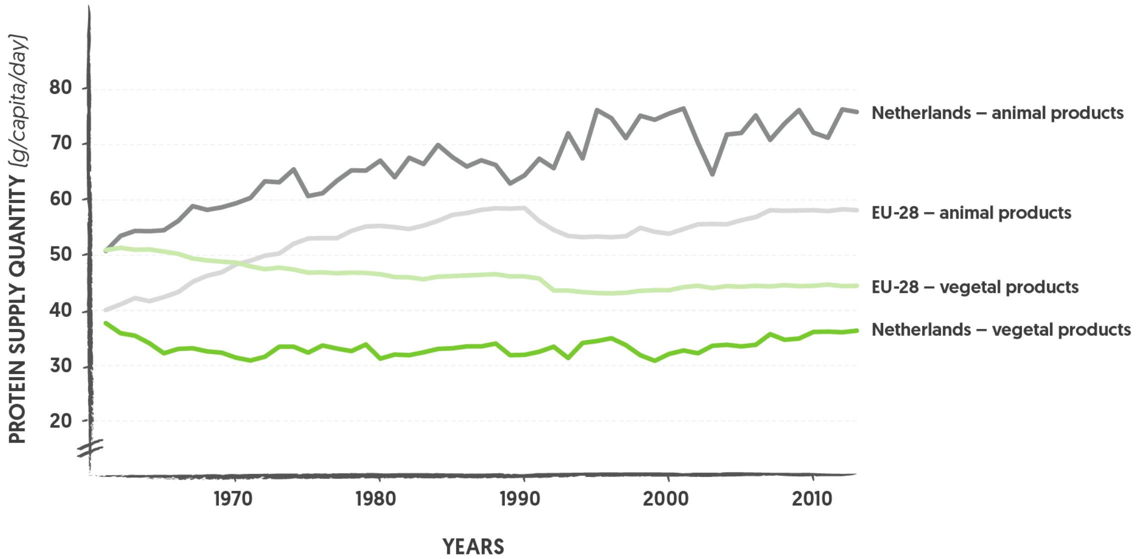

FIGURE 7. ANIMAL AND PLANT PROTEIN SUPPLY IN THE NETHERLANDS AND THE EU-28 (g/CAPITA/DAY).

In the Netherlands and the EU-28, the amount of animal protein in diets increased respectively by 10% and 13% (with an equal decrease in vegetal protein) from 1961 to 2019.

Abbreviations: EU-28, European Union: 28 countries. *Adapted from: FAOSTAT 2021. Accessed 11 March 2021.*

Food choices of individuals can also greatly affect the **waste of valuable resources and polluting emissions**. Such can be illustrated by the situation in the USA, as an extreme example of a country with a high-meat diet, which might take a first step in the right direction:

> A 25% decrease in protein intake paired with a 25% shift from animal food to plant food protein intake-from an 85:15 ratio to a 60:40 ratio-would best align protein intake with national dietary recommendations while simultaneously resulting in 40% fewer CO_2eq emissions [savings of 129 billion kilograms of CO_2eq] and 10% less consumptive water use [3.1 trillion gallons of water]. (Gardner et al., 2019, p. 1)

In addition to reduction, animal protein may be replaced by alternative proteins, such as tofu, legumes, algae, insects, or cultured meat (Godfray et al., 2019).

The EAT/Lancet Commission published actual recommendations serving the dual goal of **healthy** diets from **sustainable** food systems (The Lancet, 2019a; The Lancet, 2019b). Reducing our intake of animal protein is an important aspect of these and a multitude of similar recommendations (Birt et al., 2017; Costa Leite et al., 2020; Fischer and Garnett, 2016; IPCC, 2019; Manners et al., 2020; Springmann et al., 2018a; Springmann et al., 2018c; Springmann et al., 2020), because **direct consumption of plant protein may abolish the 85% conversion losses from plant to animal protein** (on average 6 kg of plant protein is required to produce 1 kg of animal protein as stated previously; Smil, 2000).

FOOD WASTE

In the developed world about one third of food produced is discarded in the household, rather than consumed. Consequently, the land, water, energy and N used to produce this food is also wasted. Food waste reduction is thus crucial, both at home and in the fields. Much less well-known is the fact that **overconsumption (leading to obesity) wastes even more food than the amount discarded in the household** (Alexander et al., 2017). This has sparked a prioritised list of options to improve current Western dietary patterns (Aiking and de Boer, 2020) with respect to both public health and sustainability.

N FOOTPRINT OF DIETARY HABITS

The effect of lifestyle and diets on the (virtual) N losses to the environment can be determined by a footprint model developed by Leach et al. (2012) and can be found on www.N-print.org. The footprint, expressed as N consumption and (virtual) losses to the environment per person differs per country, since the food production methods differ. Average virtual N losses for a range of countries are shown in Fig. 8. **75% of the N footprint is determined by food consumption in combination with its production.** The highest total footprint can be found in the US and Australia, mainly because of the intense energy consumption (heat, transport, industries), which is added on top of already high food-related N losses. Nr losses related to food consumption are highest in the developed countries, with Austria being the lowest. In developing countries, the footprint is much lower, as shown for Tanzania as an example (Shibata et al., 2017). This is attributable to lower consumption levels and food production with much lower N inputs. Consumption of food invariably leads to N losses since agricultural production of food in biological systems is never 100% efficient in N use. This is one of the major challenges of the N crisis: Nr losses can be reduced, but not prevented. Fortunately, the biosphere can deal with some Nr losses, though not with excessive ones. It is, therefore, key to limit these Nr losses.

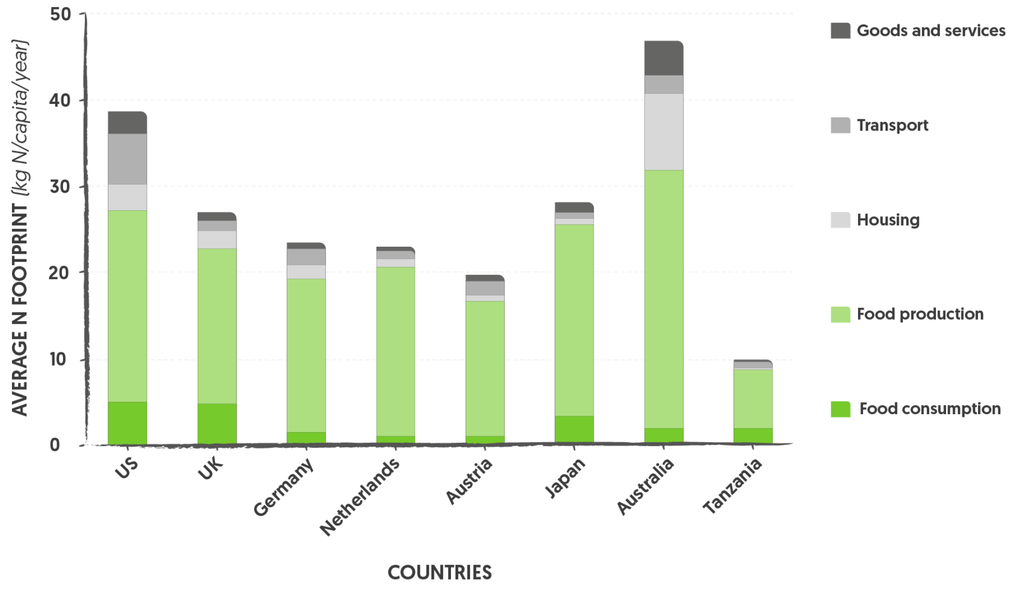

FIGURE 8. AVERAGE N FOOTPRINT PER PERSON FOR DIFFERENT COUNTRIES.

On average 75% of the N footprint is determined by food consumption and production. It represents the losses of Nr to the environment related to agriculture and fossil fuel burning. Food consumption is the total nitrogen intake corrected for treated human waste, which is converted into N_2. Especially in Germany, the Netherlands and Australia – where wastewater treatment is the norm – this results in a small N footprint due to food consumption.

Abbreviations: N, nitrogen; N_2, dinitrogen; Nr, reactive nitrogen. *Adapted from: http://n-print.org/Publications. Accessed 26 April 2021.*

ADDITIONAL BENEFITS OF REDUCING Nr LEVELS

IMPROVING HEALTH

Costa-Leite et al. [2020] show that low N footprint diets lead to improved health. Moreover, more sustainable diets are generally also healthier, as shown internationally by the EAT/Lancet Commission [The Lancet, 2019a; The Lancet, 2019b]. The food system is responsible for more than a quarter of all greenhouse gas emissions, while unhealthy diets and high body weight are among the most important contributors to premature mortality [Springmann et al., 2016]. Improving public and environmental health simultaneously provides a real win-win opportunity!

Unfortunately, few consumers comply with national dietary guidelines. Overconsumption has led to a continuing epidemic of obesity and associated diseases, such as diabetes [The Lancet, 2019b]. Overconsumption of protein is not known to be detrimental to human health [Health Council of the Netherlands, 2021]. However, proteins contain at least as many calories as carbohydrates. In addition, protein from animal source products is usually associated with saturated fat, which may lead to cardiovascular disease. Red and processed meats are known to cause certain cancers [McMichael et al., 2007]. Furthermore, the latter generally contain copious amounts of salt, which is unhealthy, as well.

LIFTING THE THREAT ON PROTECTED NATURAL AREAS

Next to a positive effect on health, a reduction of Nr levels would also benefit our valuable natural areas. European countries have joined forces via the Natura 2000 areas to protect their rare and specific species and ecosystems under the Bird and Habitat Directive. Now, N pollution is one of the most important threats to these areas (Fig. 9). This effect is mainly through deposition of ammonia, which is emitted by agriculture, and more specifically livestock farming. In addition, NO_x are released during combustion processes (burning fossil fuels) in traffic, industry, energy production or building heating. Consequently, in regions with a high concentration of roads, industry and livestock farms, substantial Nr losses to the air are evident. These are deposited on soils (by wet and dry deposition) in Natura 2000 areas. Subsequently, this causes substantial terrestrial biodiversity losses, because ecosystems are developed to optimally use the limited available natural Nr. Nutrient overload leads to soil acidification, eutrophication and promotes growth of Nr loving species. All of these cause an accelerated loss of biodiversity. To stop this negative process, a reduction of Nr levels is necessary.

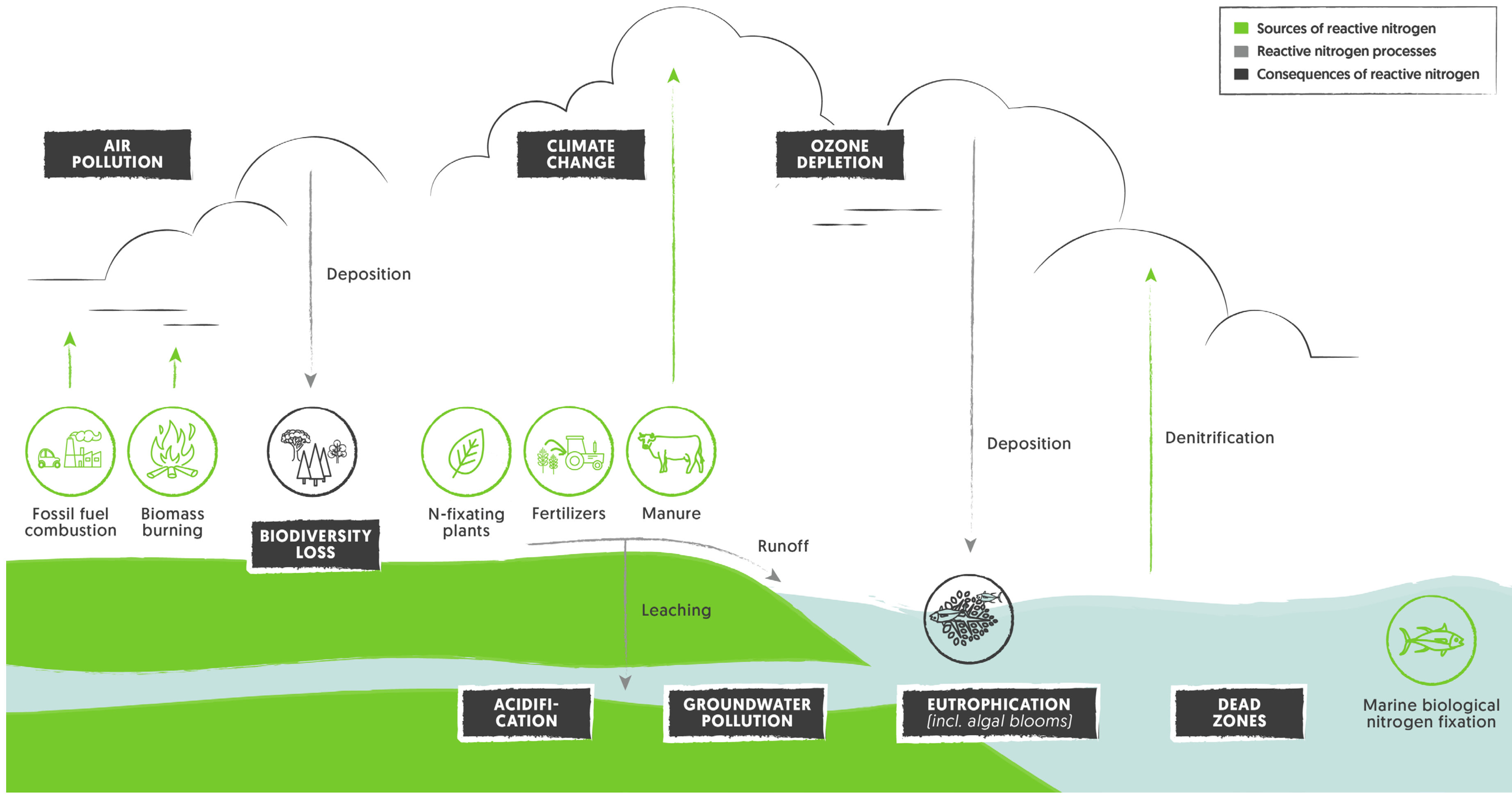

FIGURE 9. DISRUPTION OF THE N CYCLE.

The disruption of the N cycle by human activities, such as fossil fuel burning and agricultural production, leading to losses to air and water. Abbreviations: N, nitrogen. *Adapted from: Erisman et al., 2015.*

HOW FOOD PRODUCTION SYSTEMS CAN REDUCE N EMISSIONS

The 2015 Paris climate agreement translated in a Dutch climate law drives the implementation of emission reductions by the sectors that emit greenhouse gases and, additionally, NO_x. The measures to reduce greenhouse gas emissions that also reduce NO_x should be given priority. Examples are the accelerated introduction of renewable energy such as solar and wind and sustainable transport (electric or hydrogen). For these kinds of measures, there is governmental support. However, careful consideration of the possible solutions is necessary, as not all types of renewable energy also support the reduction of N emissions. For example, biomass creates extra NO_x when burned, which cannot be fully captured by forests (as they do for CO_2 released during the burning process).

OPTIONS FOR REDUCING Nr LOSSES FROM AGRICULTURE

While food waste and diets can influence the consumption of Nr and, consequently, the supply and demand side, the production of agricultural products itself can also influence the reduction of food waste and the losses of Nr to the environment. Agricultural developments have been focussed on increasing the production of food per hectare and per farmer. This has been done by increasing fertilization but also by irrigation, selective animal and plant breeding, the replacement of labour by machinery and using antibiotics and pesticides. This has resulted in increased yields.

Intensive livestock breeding is a major source of manure which, in addition to synthetic fertilizer, is an important Nr source for agriculture (Steinfeld *et al.,* 2006; Uwizeye et al., 2020). During the production, management and application of manure to agricultural fields, the N use efficiency (NUE) is low and therefore contributes substantially to Nr emissions to air, groundwater and surface water. With an average NUE of only 8% for meat consumption, most of the Nr used in producing meat and dairy is lost, whereas the efficiency of plant-based food is about 20% (Bouwman et al., 2013; Galloway and Cowling, 2002).

Improving the efficiency of N use in agricultural production systems can be achieved by introducing technology that reduces emissions from housing systems (such as air scrubbers), or field emissions during application of manure (such as incorporation of manure in grassland). Precision fertilization will reduce the use of fertilizer or, to limit losses to the environment, N fertilizer can be substituted with natural alternatives, such as biological fixation, e.g. by using leguminous crops in rotation, better use of soil Nr and better recycling of Nr (closing the nutrient cycles at different scales). In addition to technological options, circular agriculture, nature-based or regenerative agriculture and organic agriculture may be introduced to reduce Nr losses.

CIRCULAR AGRICULTURE

Circular agriculture is a form of agriculture that forms the basis for healthy food, the circular economy, the restoration of biodiversity, carbon sequestration, climate adaptation and soil, water and air quality. Closed-loop farming, or a form of agriculture that fully respects public values, makes it possible to take concrete steps in various social fields. Circular agriculture follows these principles (De Boer and Van Ittersum, 2018):

- Agriculture should primarily provide plant-based food for human consumption.
- Animals should be fed only with crop residues, residual streams or grass from marginal lands.
- Residual flows must be reused in the best possible way, successively for 1) human consumption, 2) animal feed, 3) soil improvement, 4) energy production, in that order.

In this way, the production of crops and livestock is more efficient and more direct, towards production of food for humans, and the significant Nr losses from intensive livestock rearing (entailing tremendous input of feed crops) are largely reduced.

NATURE-BASED AGRICULTURE

Nature-based or regenerative agriculture is based on agro-ecology principles (e.g. Erisman et al., 2016; Tittonell et al., 2020). Agro-ecology principles focus on the optimization of productivity (instead of maximisation) and farming practices in accordance with the characteristics of the ecosystem. This means improving resilience of the farm by making use of natural processes, strengthening functional biodiversity (such as soil quality), and protecting the ecosystem services that the farm depends on. Soil biodiversity can contribute to strengthening drought and flooding resistance and can increase nutrient efficiencies. Nr losses in nature-based agricultural systems are limited because functional agrobiodiversity and natural processes are used for production of crops integrated with animal production.

ORGANIC FARMING

Organic farming potentially can contribute to improving NUE. Losses of Nr per unit product are somewhat higher than conventional agriculture, however, because no 'new' Nr in the form of synthetic fertilizer is used, the overall NUE is higher. The production per hectare is lower, but the losses of Nr to the environment are also lower (Cattell Noll et al., 2019). Organic agriculture has other benefits for the quality of the environment, as well, since no synthetic pesticides are used and more biodiversity is maintained. Organic agriculture fits well within the conservation and development of the agricultural landscape. By using the natural processes in the production of food, the landscape and biodiversity are promoted. In doing so, the microbiology and health of the soil are improved. The European Commission in its Farm to Fork strategy aims at 25% organic farming in Europe in 2030 (https://ec.europa.eu/food/farm2fork_en).

WHO NEEDS TO DO WHAT?

The N crisis and prevention of environmental pollution and biodiversity loss require actions from all parties involved. There is an urgent need to establish the required sense of urgency, especially among governments worldwide. Furthermore, consumers can change their diets and choose healthier and more sustainably produced food. The N footprint shows that especially the change in diet towards less meat consumption and changing the ratio of animal to plant protein will have a large effect. At the same time, reducing commuting and travelling will also have a large contribution.

Farmers can change towards more sustainable practices, such as increasing crop rotations, including more dormant and N fixing crops, using more land for their animals or follow circular, nature-based or organic principles. However, farmers are usually limited by market prices, small margins and governmental regulations. Some farmers are able to implement sustainability by differentiating their products in terms of taste, quality, etc. in niche markets. Most farmers depend on the agroindustry or on the government for (financial) support. The business model of the **agroindustry** is based on growth in production: the more the farmer produces, the higher the turnover and profits of the agroindustry. The growth model holds for loans from banks, machinery, seeds, feed, products, etc. Sustainable development will require this industry to work towards new business models based on quality rather than quantity. Furthermore, there should be a shift in margins from the industry towards larger shares to the farmers to facilitate the implementation of sustainability measures.

Although numerous players in the chain have a responsibility and opportunity to make agriculture more sustainable, the **government** has a special role to play. After all, in practice it appears that the food system as a whole is unable to transform itself. The reasons for this are that we live in a free-market system and that our system of laws and regulations is not always geared towards increasing sustainability. Governments need to start with a vision on (global) markets, import and export of food and similar sustainability requirements where food is produced. This results in clear targets based on limiting climate change and biodiversity loss and preserving environmental quality.

For example, according to the European Commission, greenhouse gas emissions must be reduced by 55% in 2030 compared to 1990. Of the agricultural land, 25% must then be organic and nutrient losses should be halved. At least 30% of the land and sea must become protected areas. A carbon tax for all sectors will also contribute to reducing greenhouse gas emissions in agriculture. In part, this can be compensated by rewarding ecosystem services, when the farmer captures more CO_2 and reduces CO_2 emissions at the same time.

In addition, the government can help farmers maintain a reasonable income by providing compensation for social services they provide - for example, for nature management, water and carbon storage, or landscape management. In the Common Agricultural Policy, the government can transform direct payments per hectare into so-called eco-schemes that reward social services.

Finally, the government can improve the preconditions within the food market for farmers, and thus co-finance and promote the transition towards achieving the goals. True cost - true price systems or, for example, a tax on red meat can be used to promote sustainable farming (Springmann et al., 2018b).

The **funding** of *research, knowledge and education* also needs to be reviewed. Currently, more than 90% is devoted to technology development and knowledge to support production increases. A shift is needed towards research into ecology – as in strip farming or nature-inclusive agriculture – and **education** in sustainability, including the social sciences, in addition to the natural sciences. Particularly worthy of attention are **systems approaches** to address the interactions between soil and food quality, between food quality and health, and between health and sustainability.

CONCLUSION

The N crisis is as important as the carbon crisis (climate change). Moreover, it **embraces both climate change and biodiversity loss**. Therefore, primarily a **dietary transition from animal to plant proteins will have a beneficial impact on all three issues**. In addition, it will reduce the use of valuable resources, such as freshwater and land use and, last but not least, it will benefit human health!

Together with the change in diet, we also need **improved sustainable food production through agricultural and technology changes** within the limits of the environment, and **reduced food waste** across the food chain from production to consumption.

The awareness of these issues must be raised since the sense of urgency among politicians and consumers is low. **The N crisis in the Netherlands has shown what happens if economics prevail over preserving our natural system.** The Netherlands is the first country to have the N crisis on the political agenda. However, there will probably be more countries to follow because the judgement by the European court – which states that the quality of the Natura 2000 areas should be conserved and therefore N pollution reduced – is applicable to all the Natura 2000 areas in Europe, even though they are less N intensive than the Netherlands.

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