CODEX PLANETARIUS

Environmental and Human Impact of Nitrogen Surplus from Food Production and "Safe" Levels of Nitrogen Surplus: A Consideration for *Codex Planetarius*

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About *Codex Planetarius*

Codex Planetarius is a proposed system of minimum environmental performance standards for producing globally traded food. It is modeled on the *Codex Alimentarius*, a set of minimum mandatory health and safety standards for globally traded food. The goal of Codex Planetarius is to measure and manage the key environmental impacts of food production, acknowledging that while some resources may be renewable, they may be consumed at a faster rate than the planet can renew them.

The global production of food has had the largest impact of any human activity on the planet. Continuing increases in population and per capita income, accompanied by dietary shifts, are putting even more pressure on the planet and its ability to regenerate renewable resources. We need to reduce food production's key impacts.

The impacts of food production are not spread evenly among producers. Data across commodities suggest that the bottom 10-20% of producers account for 60-80% of the impacts associated globally with producing any commodity, even though they produce only 5-10% of the product. We need to focus on the bottom.

Once approved, *Codex Planetarius* will provide governments and trade authorities with a baseline for environmental performance in the global trade of food and soft commodities. It won't replace what governments already do. Rather, it will help build consensus about key impacts, how to measure them, and what minimum acceptable performance should be for global trade. We need a common escalator of continuous improvement.

These papers are part of a multiyear proof of concept to answer questions and explore issues, launch an informed discussion, and help create a pathway to assess the overall viability of *Codex Planetarius*. We believe *Codex Planetarius* would improve food production and reduce its environmental impact on the planet.

This proof-of-concept research and analysis is funded by the Gordon and Betty Moore Foundation and led by World Wildlife Fund in collaboration with a number of global organizations and experts. For more information, visit www.codexplanetarius.org

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Abstract

Codex Planetarius aims to protect the health and safety of the planet's biodiversity and ecosystems and the long-term health and safety of the planet's inhabitants. It seeks to do so through setting environmental performance standards for key impacts of producing globally traded food. This note considers the role of nitrogen use in agrifood systems, and the nature and scale of the environmental and human harms that result from surplus nitrogen. Traded commodities such as beef, soy, wheat, maize, rice, and cotton are associated with high nitrogen use and emissions. The scale of harm, and the impact on natural and human capital, is considerable. Economic benefits to the future from improved global nitrogen use are estimated in the order of $500 billion (USD 2015) per annum. *Codex Planetarius* could contribute to realising those benefits. However, following the *Codex Alimentarius* and determining what are "safe" levels of nitrogen surplus at a commodity level is challenging. Considerations are noted on safety needing to include sufficient nitrogen use to ensure food security and development, on the quantification of performance standards at the point of application, emission, harm, or social cost, and on the burden of compliance on producer, trader, or government.

Introduction

Nitrogen as the inert gas N_2 forms 78% of the earth's atmosphere. Nitrogen flows from the atmosphere to a myriad of reactive nitrogen compounds in soil, water, plants, animals, and humans are essential to life and society. The strong chemical bond in N_2 has, for most of human history, limited the availability of reactive nitrogen that can be used in terrestrial organic and inorganic processes. The invention of the Haber-Bosch process in the early 20th Century made reactive forms of nitrogen such as ammonia and nitrate available on an industrial scale.

Anthropogenic Change of the Nitrogen Cycle and the Agri-Food System

Natural deposition of reactive nitrogen from the atmosphere by lightning and biological fixation from nitrogen producing plants were the major pre-industrial sources of reactive nitrogen for terrestrial processes **[1, References, page 18]**. Industrial processes have doubled the flow of the global reactive nitrogen cycle [2]. Most of the new nitrogen added to the global cycle concentrates in agriculture. From 1960 to 2010 cropland area increased by 20%, while the flux of nitrogen from synthetic fertiliser to cropland and losses have increased 700% in the same period [3] **(Figure 1, page 11)**. With the increase in population by 2050, it is expected that the flux of nitrogen through cropland and pasture is likely to double again [4, 5].

The human species has greatly benefited from changing the global nitrogen cycle. From 1900 to 2020 global population grew from 1.6 billion to 7.8 billion individuals. It is estimated that half of the current food consumption is supported by the Haber-Bosch process [6]. Habitats have also been spared from cropland expansion, as supporting the same population without synthetic fertiliser would require cropland to cover 25%-40% of all terrestrial land instead of 15% [1].

However, utilisation of the available nitrogen in agriculture is inefficient. Over 50% of the nitrogen in fertiliser and manure applied on fields is lost to the environment [7, 8]. The biosphere is the sink for losses. As a result of the anthropogenic alteration of the nitrogen cycle, in most regions reactive nitrogen is available and accumulating in the biosphere at a level unprecedented in recent geological history [2, 9].

Fertiliser, manure, and agricultural soils emit ammonia, nitrous oxide, and smaller amounts of nitrogen oxides to the atmosphere. Fossil-fuel production and burning in combustion engines emits small amounts of ammonia and larger amounts of nitrogen oxides. Agriculture, food manufacturing, and food retail are associated to 80-90% of anthropogenic ammonia (NH3) losses and around 20% of anthropogenic nitrogen oxides (NO_x) losses [2, 10-14]. Agriculture is responsible for around 70% of anthropogenic emissions of the greenhouse gas N_2O [15-17] and 80% of the reactive nitrogen that ends up in waterways [2, 18]. Half of the NO_x emissions and N_2O emissions of the food system are from microbial processes in soils [19]. The other half of the agri-food system NO_x emissions are from fossil fuel production and burning for energy and transport [20, 21]. While ammonia NH_3 dominates reactive nitrogen losses to atmosphere from food systems in advanced economies, NO_x is still prevalent in developing countries due to agricultural practices such as burning, transport in the food system, and cooking [22].

Processing and manufacturing of food products result in <2% of agri-food system direct reactive nitrogen losses, or “Scope 1” losses [23]. For food processors, manufacturers, and retailers, “Scope 2” emissions of NO_x occur in energy and transport [14]. “Scope 3” nitrogen losses occur upstream in agriculture (>90%) [24], and downstream in human waste post-consumption (<10%) [25].

Livestock production **(Table 1, page 17)** including feed accounts for 62% of the reactive nitrogen losses from the agri-food system, which is around 33% of global losses across all anthropogenic sources [23]. Losses across chemical species of nitrogen are measured by the molecular weight of nitrogen in the species. Livestock provides 17% of global calories and 33% of global protein [FAOSTAT] [26]. Crops for human consumption and horticulture account for 35% of the reactive nitrogen losses from the agri-food system [27] and provide 82% of global calories and 60% of global protein [FAOSTAT].

Impact on Natural and Human Capital

The damages of reactive nitrogen losses from synthetic fertilisers and livestock range from air pollution in densely populated areas to biodiversity losses along waterways and coastal ecosystems [28, 29].

Ammonia (NH_3) losses as a gas to atmosphere create fine particulate matter (PM2.5) through chemical interactions with nitrogen and sulphur oxides [29]. Exposure of human populations occurs through wide dispersal resulting in human respiratory disease, cardiovascular disease and cancer, and subsequent productivity losses [30, 31]. The heavy ammonium compounds eventually fall from the atmosphere onto land and water, called deposition [28]. The deposited compounds can undergo secondary chemical reactions, resulting in acidification and secondary emission of nitrogen oxides (NO_x) or the greenhouse gas nitrous oxide (N_2O) to the atmosphere or run-off into water ways [32]. In water ways, reactive nitrogen, eventually mostly in the form of soluble nitrate (NO_{3-}) [33], causes acidification and eutrophication in riverine or coastal ecosystems [34-37], can impact humans and animals through nitrate pollution of drinking water [38, 39], and also re-emits nitrogen gases to the atmosphere [40].

Nitrogen oxides (NO_x) emitted to the atmosphere have a similar pathway to ammonia. They create fine particulate matter (PM2.5) and deposition which results in acidification, eutrophication, and secondary emissions [28]. With NO_x and SO_x regulation on transport emissions in advanced economies, agricultural ammonia NH_3 has become an increasing and major source of air pollution [41], causing up to 15% of air pollution deaths in the US [42] and up to 30% in some Chinese cities [43]. Additional to particulate matter, NO_x creates ozone in the lower atmosphere [44]. Ozone in the lower atmosphere is highly damaging to vegetation including crops [45].

Nitrous oxide (N_2O), whether direct from soils or in the cascade of nitrogen reactions from NH_3 or NO_x emission, is a greenhouse gas and reduces stratospheric ozone [46]. Unlike the reactions to NH_3 and NO_x emissions, and NO_{3-} run-off and leaching, N_2O is almost inert in the atmosphere. A molecule can add to radiative forcing for over 100 years [47], contributing to the human and natural capital impacts of climate change [48]. Nitrous oxide (N_2O) is now the most significant ozone-depleting substance (ODS) and is projected to remain so throughout the 21st Century [49]. Impacts of NH_3 and NO_x emissions, and NO_{3-} run-off and leaching, outside of indirect N_2O emissions have different temporal dynamics than the impacts of climate change and slow breakdown of N_2O in the stratosphere [50]. The differences are relevant to economic evaluation of the costs of nitrogen losses, to policy, and to mitigation of impacts.

Ammonia and nitrogen oxides create compounds that last for days in the atmosphere, leading to respiratory disease which impacts human capital in the weeks to years after exposure [51]. Acidification and eutrophication occur days to weeks after run-off or deposition with seasonal effects on crop growth or water quality [52]. For N_2O, the same molecule becomes part of a stock of gases that contributes to warming for a century. For the other species of reactive nitrogen, especially NH_3 and NO_x, one molecule initiates a cascade of molecules with multiple impacts on human and natural capital in the time frame of years [2]. Cumulative damage to human capital from air pollution and to ecosystems from nitrogen loading occurs through repeat exposure [53, 54]. Additional nitrogen makes some plants grow more than others through provision of nutrients and changes in soil chemistry [55]. Changes in vegetation lead to changes in the trophic structure (the other plants and animals) of the ecosystem leading to alteration [56]. In the example of eutrophication, algae (plants) proliferate, leading to hypoxic and anoxic conditions for vertebrates and mass fish kills [57, 58]. Sustained events can create long-term, and potentially permanent, changes to the trophic structure and ecosystem.

Nitrate NO_{3-} has impacts from annual flows and stocks. Reactive nitrogen is being produced more rapidly than it is being converted back to inert N_2 [28], leading to the risk that terrestrial and marine sinks saturate [59-61]. Enhanced exposure from saturation and increasing vulnerability in humans and ecosystems from repeated over-exposure imply that, all else being equal, the human and natural capital impacts will increase even if current annual loading from NH_3, NO_x, and NO_{3-} were to remain the same (legacy effects [62]).

Interactions

With carbon and methane cycles

Nitrogen and carbon are Earth’s major geochemical cycles. The doubling of the nitrogen cycle has altered aspects of radiative forcing in the atmosphere and carbon dioxide sequestration [63, 64]. Increased nitrogen in the biosphere has increased carbon sequestration in biomass alongside biodiversity loss [65]. It is estimated that the ocean biomass has increased >3% due to deposition of anthropogenic nitrogen on open ocean [60], increasing the ocean’s sequestration capacity [66]. Ammonium compounds and other particulate matter formed from NH_3 and NO_x are aerosols that increase albedo in the atmosphere, which reduces warming [67]. There are interactions with the methane cycle, such as the production of ozone from NO_x increasing concentrations of the OH radical and contributing to methane CH_4 removal [68]. In terms of historical radiative forcing, non-N_2O emission have had up to twice the negative radiative forcing effect compared to the positive radiative forcing from N_2O emission [69]. In terms of future temperature potential, over the short term (20 years) the additional cooling effects of a year’s worth of non-N_2O annual anthropogenic nitrogen emissions potentially negates the temperature increase from a year’s worth of N_2O emitted in the GTP-20 metric [67].

With biodiversity

Nitrogen loading on ecosystems nitrogen makes some plants grow more than others, leading to changes in the trophic structure of the ecosystem, leading to biodiversity loss and alteration of ecosystem functioning [56, 70]. Loss of habitat from agricultural land expansion, nutrient losses from agriculture, pesticide losses, and climate change are major anthropogenic sources of biodiversity loss in natural habitats [71, 72]. Sustainable nutrient management for biodiversity protection has captured intergovernmental attention under the UN Convention on Biological Diversity (CBD). Target 7 of the intergovernmental Kunming-Montreal Global Biodiversity Framework requested countries to halve their nutrient waste from all sources by 2030.

Economic Impact

Anthropogenic alteration of the nitrogen cycle has contributed to sustained exponential economic growth through food provision and freeing labour from primary production [73]. However, excessive nitrogen emissions also impact the economy from the changes in natural and human capital [74].

Hidden deficit from nitrogen emissions

The United Nations (UN) system of national accounts does not subtract the future liability of damage to human and natural capital from gross product [75]. Any future losses to the national economy, or the economy of other nations, from activity in agri-food sectors in the current year is unaccounted for. Economic losses beyond the year of nitrogen emission occur from labour productivity losses from air pollution and loss of services from degraded ecosystems [76].

Separate studies from the Food and Land-use Coalition (FOLU) [77], the United Nations Food System Summit (UNFSS) [78], the United Nations Food and Agricultural Organization (FAO) [79], and the Food System Economic Commission (FSEC) [80], have placed the future losses from agri-food activities in a single year in the order of $10-15 trillion (USD 2020) in present purchasing power, an 8%-10% correction to a single year of GDP in 2020. Roughly 8-10% of GDP is also the estimate of the global value added from agri-food economic activities [77]. If the trends of current diets and production methods continue, then the future losses accumulate year on year as a hidden deficit. An accumulating liability of the size estimated puts at risk global economic development and sustainable growth.

Estimates of the cost to future gross product from agri-food sector nitrogen emissions in a single year are around $1 trillion (USD 2020) in present purchasing power. The costs are of the same order of the costs of agri-food sector carbon dioxide and methane greenhouse gas emissions. These estimates come from the FAO and FSEC reports [81, 82]. Estimates of damages in previous literature [76, 83] and the forthcoming global report of the International Nitrogen Initiative [84], are in the same range. Economic reports of the future and unaccounted costs of climate change such as the Stern report [85] mainstreamed carbon taxes, emissions trading, and other policy instruments. However, there have been few similarly influential investigations across all the damages associated with food production and consumption, including nitrogen.

Benefits of mitigating nitrogen emissions

The existence of a liability does not imply it is avoidable. Producing and consuming food in other ways could end up costing more to implement than the cost of the pollution it would reduce. For nitrogen, this scenario is unlikely for most producer countries outside of Africa [86]. One study found $20 billion (USD 2015) of abatement measures could reduce nitrogen pollution on global cropland by 33% with a benefit from avoided damages estimated at $480 billion (USD 2015) [87]. There was no reduction in yield. Similar figures of avoided damages in the order of $520 billion (USD 2020) PPP were found for the FSEC food system transformation pathway [82].

Realising the economic benefits of reducing nitrogen emissions will rely on navigating effective transfers between beneficiaries and cost bearers, of pollution or abatement. Producers are the primary nitrogen polluters. The weight of nitrogen regulation, real or perceived, has fallen on farmers [88], without full regard for their ability to pass the costs downstream to traders or retailers [89]. Retailers, and governments, also face difficulties on taxing consumption [90-92]. Consumers have become accustomed to the consumer surplus that low costs of food have afforded. Current short-term political cycles have low tolerance for reducing consumer surplus. Not accounting for future liabilities in national accounts has created part of this trap. By not mainstreaming the economics of social and environmental costs through established economic facilities such as productivity commissions, the system has failed to gradually expose the economy to corrective costs and actions.

Considerations for *Codex Planetarius*

Nitrogen emissions from food production are one of the primary drivers of biodiversity loss, human air pollution, and at least 20-30% of nitrogen emissions involve traded commodities. The enormous flux of nitrogen through agricultural land and activities, the reactivity of nitrogen to biological and chemical process on Earth, and the shorter-term nature of nitrogen impacts, means that the economic damages in present purchasing power resulting from nitrogen emissions from food production are of a similar order to the damages from CO_2 and CH_4 emissions from the same activities. By these measures, nitrogen surplus would be accounted as a key impact of globally traded food production alongside CO_2 and CH_4 emissions.

While greenhouse gas emissions are recognised as an international issue and a problem of the global commons, nitrogen emissions outside of N_2O have less recognition in international treaties and among actors such as multi-national traders, manufacturers and retailers. *Codex Planetarius* presumes that the performance standards are recognised amongst trading states as a global commons issue requiring international cooperation. To support the inclusion of nitrogen performance standards in *Codex* and acceptance amongst states and actors, global commons arguments for nitrogen are provided below.

Another challenge for including nitrogen performance standards in *Codex* is the specification of standards at a commodity level. The complex and context dependant pathway of nitrogen from application to emissions to multiple routes to impacts and economic damage introduces competing considerations for which point along this pathway performance should be set and for which actors should be targeted for compliance. Without providing a definitive answer, nor quantitative prescriptions, measurement of performance is explored below.

Another premise of *Codex* is that performance can be improved by mitigation of nitrogen emissions and adaptation. Studies affirm that cost-effective mitigation of nitrogen impacts is available. However, political-economy and behavioural hurdles have prevented global implementation of these measures, even the ones which are, conceptually, Pareto efficiencies and in the self-interest of producers. *Codex's* argument and appeal to states and actors could be enhanced with insight into achieving abatement, meeting standards, co-ordinating solutions, and especially effective transfers between the beneficiaries of improved performance or pollution and those, mainly producers, bearing the costs in meeting the standard.

If these challenges can be addressed, then *Codex* would act as a corrective mechanism for reducing nitrogen emission toward safe planetary levels. It would potentially spillover to improved performance for food production that is domestically consumed.

For *Codex*, the implication of the interaction between the nitrogen and carbon cycle is that performance standards for greenhouse gas emissions (CO_2, CH_4, and N_2O) and non-N_2O nitrogen emissions are a joint consideration. Conceptually, achieving performance of the nitrogen standard would reduce some global cooling effects, requiring a higher bar on the greenhouse gas performance standard to compensate. If a 100-year equivalence to the cooling effect is chosen, this could be reflected in a higher standard for CO_2 emissions. If a short 20-year equivalence for the cooling effect is chosen, this could be reflected in a higher standard for CH_4 emissions. Practically, the lost cooling effect from reducing nitrogen emissions is small compared to the heating contributions of CO_2 and CH_4 at present emissions. *Codex* should note and consider all interaction effects, including that of reduced impacts of land-use change on both climate and nitrogen impacts, but, once noted, and insofar as the interaction between the carbon and methane cycles and the nitrogen cycle, the small level of compensation in the CO_2 and CH_4 performance standards for achieving the nitrogen performance standard could be omitted from a first iteration.

Global Commons

National emissions of well-mixing greenhouse gases (GHG) have global climate impacts through atmosphere, and they are recognised as a global commons issue [93]. Despite nitrogen assessments in major economies, including the European Nitrogen Assessment [94], California Nitrogen Assessment [95], Indian Nitrogen Assessment [96], an upcoming Regional and Global Nitrogen Assessment [97], and resolutions of the United Nations Environment Assembly [98], there has been less international focus on the nitrogen problem [99, 100]. *Codex* would sit as one of the instruments within the global cooperation needed on nitrogen emissions.

Nitrogen's major role in biodiversity loss and N_2O emissions are global concerns. Some nitrogen effects are local and regional [101]. Nitrate run-off and leaching extends downstream through water catchments and can cross national borders and coastal zones. PM2.5 generated by NH_3 and NO_x emissions can be dispersed more than 500km from the point of emission, depending on air plumes [10, 51]. Deposition rates are very high across Europe and Southern and Eastern Asia [102-104]. As an example, Bhutan has deposition on cropland from NH_3 and NO_x emissions in India and China that exceeds domestic application of synthetic fertiliser [FAOSTAT].

The Gothenberg Protocol recognises the transboundary problem of nitrogen gases leading to air pollution. While it has common pledges for reduction, mostly NOx for combustion and fossil fuel burning with only small targets for ammonia 6% [105] despite the cost-effectiveness of NH_3 abatement [106], the protocol has few common instruments. Guides provide common advice for the 24 signatories in Europe and North America. China, India, and Brazil are important additional members required in global nitrogen conventions. China has approximately 30% of global nitrogen and pesticide use on 9% of global agricultural land [107, 108].

Despite the variation in the local-to-global scale of impacts across nitrogen species and forms of pollution, the world's leading scientists on nitrogen through the International Nitrogen Management System (INMS) and the fifth session of the United Nations Environment Assembly have called for a total nitrogen approach [109-111]. Features of the nitrogen problem, and the actions needed to balance the benefits and costs of nitrogen use in the food system, provide a range of arguments for nitrogen as a global commons issue beyond transboundary impacts:

Highly traded commodities including soy, maize, cotton, coffee, and beef involve most of the surplus from synthetic fertiliser application and manure [112, 113]. International footprint of imports creates a commons issue needing international dialogue and agreement.

Losing competitive advantage and the perception of losing sovereign food security can deter first movers in reducing agricultural nitrogen losses. Reducing losses without retaining yield reduces productivity and would lead to the displacement of production to countries or regions not similarly moving to reduce nitrogen losses. Common commitments to reduction in nitrogen losses among major agricultural producers allows countries to move and compete on nitrogen use efficiency. Including moving N-inefficient agricultural activities, with larger losses to soil, air, and water to regions less prone to negative impacts [114].

Changes to nitrogen use are relevant to global cooperation for food security. No alternative technologies exist today that could feed the current global population within current agricultural land or land that could be feasibly converted to agricultural use.

There is competitive advantage for producers to optimise the cost of synthetic fertiliser inputs against increase in yield by improving nitrogen use efficiency. However, larger producers and wealthier or subsidising countries can be less sensitive to costs of synthetic fertiliser input against farm-gate revenue from increased yield [115]. International coordination on input subsidies based on yield gaps and nitrogen use efficiency would improve competitiveness [116].

Many low income or isolated countries lack the capability to model nitrogen flows and impacts and assess benefits in abating nitrogen losses [117-119]. Broad acceptance of measurement for targets for nitrogen losses may require a global facility that aids measurement for smaller- and lower-income countries. Such a facility could also inform targets by common assessment of benefits and costs of nitrogen use. Some countries, especially in Africa, would benefit from using more nitrogen and can tolerate losses, while some countries gain only marginal additional benefit from further nitrogen application and need to reduce nitrogen losses. Political acceptance of country-specific targets that allow some countries more leeway while restricting other countries requires an accepted common assessment. Economic instruments such as levies would also need a broadly accepted analysis.

The number and heterogeneity of agricultural producers is a barrier to dissemination and uptake of knowledge on nitrogen use efficiency [120]. A global forum and facility to share knowledge on common barriers for smallholders would improve competitiveness.

There is an inability of cost-bearers of impacts from nitrogen losses to gain redress from cost-producers (polluters). Cost-bearers and cost-producers can be separated across years, across jurisdictions, and in many cases have unequal power to access existing regulatory or legal channels for redress. Global compacts are common vehicles for rights of present and future peoples, in this case the rights of cost-bearers of the externalities of agricultural nitrogen pollution. Outside of a partnership such as UNEP GPNM, there are few global nitrogen forums for impacted people to share their experiences and observations of the impacts on their ecosystems. The International Nitrogen Initiative provides the best scientific forum for environmental concerns on nitrogen while the UNEP Working Group on Nitrogen, established to implement the UNEA resolutions 4/14 and 5/2 on sustainable nitrogen management, have representatives from about 100 countries and growing.

Low-productivity farming practices are also among the most polluting, with economic necessity driving agricultural expansion and habitat loss, and the use of low-quality inputs (urea fertilisers) [86]. Low productivity hits standard economic development in the present. The growth of countries with a high economic reliance on agriculture but low productivity will be double-hit as the environmental and public health costs of current practices come to maturity. Managing nitrogen performance is an issue of international development.

Benefits of pollution accrue for multinational commodity traders, global food manufacturers, and retailers. Without global agreements, multinational entities can circumvent the attempts of individual countries to impose costs for reducing nitrogen losses.

Mitigation and Adaptation

Actions which prevent NH_3, NO_x, N_2O, and NO_{3^-} emissions to air or waterways can be termed mitigation. Actions which reduce impact after the emissions have occurred are adaptations. Riparian zones, manure management, improvements in nitrogen use efficiency without increases in application rates, are examples of mitigation measures. Human populations wearing masks for air pollution or moving intensive fertiliser application and livestock further from population centres are examples of adaptations. Overall, the extent of diffuse emissions from agricultural systems and the evolved reactivity of human and natural systems to available nitrogen make adaptation options limited.

Mitigation

There is a large potential for mitigation of nitrogen losses to the environment through efficient use and nutrient recycling [121]. Increasing biological fixation as a nitrogen source through rotation or intercropping with nitrogen fixing plants, organic production methods [122], or manipulation of cereals to increase their innate nitrogen fixing [123], can reduce synthetic fertiliser use and reduce overall nitrogen pollution [87]. Mitigation measures, including nutrient recycling and crop rotation [124], especially for livestock, can be expensive for small-scale farmers [125-127]. Some mitigation measures relate directly to the cost difference between mineral fertilisers. Urea fertilisers are more polluting without specific management [128], but cheaper than ammonium nitrate and more available in developing markets [129]. Nitrogen-use efficiency measures often emerge as the most promising mitigation options [88, 121]. Outside of nitrogen use efficiency, dietary change with less animal foods offers considerable mitigation potential [3, 130].

Efficiency in abatement is also a key consideration for the cost-effectiveness of large-scale nitrogen transitions [87, 106, 131]. Farm size is often correlated with increased nitrogen use efficiency and increased scale for better quality inputs and nutrient management practices [132]. Paying the abatement cost for generational transition of smallholder livelihoods, or for successful collectives that are able to operate at the efficiency and have the scale advantages of larger enterprises [133], could potentially be cheaper than additional nitrogen efficiency amongst those already efficient.

As part of *Codex*, trading nations might set mitigation targets for nitrogen emissions and translate the targets into safe rates for relevant commodities. Who to target with compliance is an important consideration for efficient abatement [134]. While producers are the primary nitrogen polluters they are not the primary beneficiaries of production [135]. Targeting the concentrated actors in global trading and manufacturing instead of the heterogenous producers has the potential to reduce public cost of compliance, negate leakage, utilise the scale of the multinational actors in the value chain, and accelerate adoption of uniform measurement and private compliance practices [136]. The concentrated actors at the trading level provide an initial target for the high value and heavily traded commodities [137]. These actors can either pass costs of compliance downstream to consumers by higher sale prices or upstream to producers by offering lower farm-gate prices, or both. This approach has parallels with emission targets for NO_x and SO_x for global manufacturers of vehicles. Manufacturers like the Volkswagen group bore the penalty for lack of compliance. Costs of compliance passed upstream to small scale food producers by traders have the potential to be offset by fertiliser savings and public payments for avoided societal damages.

Who pays for mitigation?

“Polluter pays” is a principle based on compensation for damages incurred or the infringement of rights [138]. Beneficiaries of the pollution should compensate cost-bearers [139]. However, to incentivise obtaining a potential $500 billion (USD 2015) social benefit for a $20 billion (USD 2015) cost, there is an alternative where beneficiaries of the abatement compensate cost-bearers of abatement [140].

Future tax-paying beneficiaries of abating nitrogen emissions are across society due to the reduction of diffuse air pollution and provision of ecosystem services. Public bonds are one type of instrument where future beneficiaries across society provide funds in the present for abatement.

One of the barriers to achieving change through the “polluter pays” principle is the entrenched marginal economic capacity of farmers to afford effective nitrogen reduction measures [141]. Public bonds or advanced abatement commitments can support economic incentives such as loans paid off by abatement. The difference with being paid directly for abatement is the availability of initial capital. As national abatement nears targets then the available funds naturally decrease and become self-limiting. Where the social costs of nitrogen are negative, then such a facility invests in increasing agricultural use of nitrogen.

Measurement

What are safe levels of nitrogen emissions, and could they be tied back to the products or primary activities of agriculture as performance standards? For exploring implementation of *Codex*, considerations for setting performance standards at a commodity level is discussed below.

For consistency in *Codex* with greenhouse gas emissions (GHG), it is expected that performance standards for nitrogen have the format of a vector of nitrogen emissions per metric ton of the traded product. Schemes for key impact measures across greenhouse gas emission, water use and land-use change propose similar consistency [142]. For nitrogen, emissions are not the only option for performance measurement. **Figure 3 (page 13)** is an alternative conceptualisation of the impact pathway of **Figure 2 (page 12)** used in environmental management and reporting standards such as the Natural Capital Protocol [143]. Performance measurement at point of activity, point of emission (output), point of impact, and point of economic cost bearing from impacts, is examined in this section. Additional rationale for translating performance back to emissions is mentioned.

Options for setting performance standards for emissions at a commodity level have the following common elements. Identify a limit for total emissions based on activity levels, biophysical impacts, or economic cost-bearing, respectively. Then identify an allocation of the limit of total emissions to emission per commodity per metric ton. Each option for limit and allocation has advantages and disadvantages, and each offers a different rationale at the commodity, geography, and development level for the risk of exceeding the limit or the risk of restricting too much the benefits of nitrogen application. Preferably the approach of *Codex* is consistent across the key environmental impacts of greenhouse gases, nitrogen pollution, water use and land-use change. All environmental sources of impacts have similar schematics to Figure 3 even though the details of their respective impact pathways differ from nitrogen.

Risk assessment of traditional pollutants determines safety thresholds for output concentrations in air or water based upon impacts [144]. Excess concentration is often traced back to inputs to an industrial process, which can target regulation on economic activities such as monitoring outputs, limiting use of inputs, or banning processes if alternatives are available. Some point-source nitrogen pollution from agri-food sources can be treated similarly. National monitoring of NO_x and NH_3 emissions to air and nitrate pollution in waterways has sponsored regulations on fertiliser application and manure management to minimise losses. Large farms and intensive livestock operations approximate point-sources of pollution, which are more amenable to successful regulation. Existing regulation focuses on best agricultural practices and compliance with them [88], rather than a focus on setting and monitoring safe rates of emissions. Direct monitoring and compliance of emissions at the farm level for an instrument like *Codex* is constrained by cost. In literature on the economics of non-point source pollution, limits for total emissions are a form of exogenous or ambient target setting [138, 145]. From an economics viewpoint, allocation concerns the efficiency by which the different pollution levels or impacts of individual emitters can be represented by the instrument [145, 146]. Efficiency in allocation is challenging for impacts. In studies of nitrogen emissions across the same US state, costs of impact per emission showed order of magnitude differences [147].

For nitrogen, safe is a double-ended term, meaning limiting emissions from surplus while ensuring sufficient use for food security and economic security.

Safe rates according to biophysical criteria

Basing safe rates on biophysical criteria involves determining the thresholds at which the damage to natural and human capital from additional emissions becomes detrimental [148]. Detrimental requires a scientific and political determination and consensus. The planetary boundary thresholds for nutrient emissions are based on critical risks to people and the risk of generating large-scale abrupt or irreversible environmental changes [149]. Regional planetary boundaries for nitrogen emissions are more appropriate given the spatial variability of nitrogen loading, saturation, and exposed and vulnerable human populations and ecosystems [9]. Translating total agricultural nitrogen emission targets such as regional planetary boundaries to commodities requires allocation [150]. Allocation based upon current share of overall agricultural nitrogen emissions in a region would translate to a uniform percentage reduction across commodities in that region to achieve the regional target. Deviation from uniform reduction implies prioritisation based upon economic, business, nutrition, or food security criteria, or other criteria that take potential co-benefits or adverse effects into account. For example, if nitrogen emissions from specific production systems occur in the vicinity of high-nature value areas, commodities from these systems could be allocated a higher reduction share. Allocating among commodities based upon current share of value-add from production or differences in costs of reduction implies economic weighting in the allocation. Allocation based on natural units such as hectares for crops and tropical livestock units for livestock would spatially or biophysically prioritise efficient nitrogen use of land and animal resources. An allocation for a commodity can be divided by production volume, translating the overall threshold into a rate such as a threshold level of N-kg of ammonia emission per kg of the commodity measured in the weight of its production volume.

Competing interest in allocation is likely the main barrier for broad acceptance of nitrogen emission in *Codex*. Rates should be nationally, or even sub-nationally, set for context in all three components of overall threshold, allocation of emissions, and amount of production. Rates would also need to be updated on regular basis, reflecting improvements in efficiency, changing priorities or shares in allocation, and changing thresholds due to a decrease in transport and industry NO_x and NH_3 emissions or natural or human capital conditions. Competing interests for allocation have market and trade implications, as different choices can create different rates and competitive advantage based just on allocation. Rates based on target trajectories that gradually introduce emission constraints can be normative or responsive, the former seeking to shape production while the latter is agnostic as long as aggregate production stays within thresholds.

Safe rates from thresholds like the planetary boundaries put an upper limit based on damages to natural and human capital. There is a potential lower limit based on the societal benefits of nitrogen application, including food supply. Macro-nutrient self-sufficiency in watersheds is one biophysical criteria to estimate a lower limit of nitrogen input needs and corresponding allowable emissions [18] (the lower limit may be infinite for watersheds where adequate macro-nutrients for human demand needs are greater than maximum production at saturating fertilisation). Macronutrient self-sufficiency is not an optimal criterion from a resource, micronutrient, or economic perspective. Incorporating imports and exports, optimality, and economic criteria for development is discussed in the next section on marginal costs and benefits. In contexts where the food security limit (meeting minimal macro-nutrient needs) exceeds the planetary boundary limit, a way to resolve the trade-off is to give the food security limit precedence. This is simple in conceptual terms but may create political complications if countries claim food security needs to reduce or remove the performance level of *Codex*.

Marginal costs and benefits of abating nitrogen emissions

Allocating reductions among agricultural activities by biophysical criteria becomes complicated if the economic value of exports and disparities among actors in the costs of reductions are considered. Competing interest between the utility of the agricultural activity enabled by permitting nitrogen emissions and the disutility of air pollution and environmental harm is represented in economics by marginal costs and benefits. Considering the trade-off point between the costs and benefits is one approach to allocation. Those that cost more, in terms of net cost, should mitigate more.

To align with the concept of hidden deficits to future growth and development, costs and benefits are to gross product in present purchasing power. In most nitrogen literature, the economic balance between the present value of the agricultural production-enabled value of additional nitrogen emissions (as surplus to nitrogen application) is compared to the present value of the costs of impacts to natural and human capital from the additional emission [151]. This provides a quantity of emissions for which the benefits of additional emissions to production are no longer worth the costs of impacts **(Figure 4, page 14, bottom panel)** [152]. However, before advocating this quantity of emissions as a limit on total emissions based upon economic criteria we discuss flipping the notion as done for climate change economics and the abatement of greenhouse gases.

Consider what is the value of additional reduction of nitrogen emissions (Figure 4 top and middle panel). Costs and benefits are flipped, so in this case the benefit of additional reduction of nitrogen is the marginal value of the avoided costs to natural and human capital. The costs are the marginal costs of achieving that reduction of emissions. What is relevant about flipping from addition of nitrogen emissions to abatement of nitrogen emissions is that loss of agricultural production is not the cheapest way to reduce the nitrogen emission. It avoids a false dichotomy between emissions reductions and production loss. Nitrogen use efficiency and other nitrogen pollution mitigation measures may be cheaper than lost production for many countries not at the top of the yield curve. Using nitrogen abatement curves instead of just the cost of lost production, the intersection between the marginal abatement curve and the marginal benefits from avoided impacts may occur at a lower level of emissions (Figure 4 middle panel). Society profits more at the lower level of emissions (Figure 4 top panel).

The quantity of emissions where the marginal benefits of avoided impacts due to abatement meets the marginal cost of abatement is a target for nitrogen emission reduction based on economic criteria (Figure 4). From an economic perspective, as economic costs for food security such as lost productivity from reduced production are conceptually in the abatement curve, the economic target is balancing the trade-off between impacts on natural and human capital and food and economic security. For some countries the balance point might involve negative reduction, which is an example of a negative social cost **(Figure 5, page 15)** [9].

A negative social cost to nitrogen indicates that needs for food security exhaust cost-effective nitrogen use efficiency measures to create greater yields in that country and that costs of impacts from additional emissions are lower than the value of additional production from those emissions. This would be expected where poverty is high, agricultural productivity is low with significant barriers to improvement, and additional nitrogen from agriculture is not yet saturating the biosphere. From an economic perspective, current nitrogen emissions in countries with negative social costs are still below safe levels and could increase. Cost-effective increases in nitrogen use efficiency are still accounted for (Figure 5 middle panel cf. bottom panel).

Using an economic target for nitrogen emissions has advantages for allocation. Abatement curves are a prioritisation of cost-effective reduction. Emissions reduction can be allocated based on abatement curves where there are abatement measures that are specific to a commodity. As for biophysical criteria, once an overall target trajectory toward optimal levels is allocated, then rates follow from production volumes. A major barrier in using the social costs of nitrogen for target and rate setting is the information required to calculate marginal benefits of avoided impacts and the abatement curves. Benefits of avoided impacts from nitrogen emissions can be highly uncertain due to lack of economic knowledge of the value of ecosystem services and how nitrogen loading affects those services. Estimates of the benefits of reduced impacts on humans and ecosystems are often based on stated preferences, which can be volatile and not directly comparable with revealed market costs and benefit.

Abatement curves also suffer from uncertainty, as they require projecting the amount of reduction in emissions and the direct and indirect costs of explicit national abatement measures available to countries. The granularity of abatement, or any allocation method, could apply to production methods within a commodity, e.g. grass-fed extensive beef production versus intensively finished beef. Including co-benefits of extensive production would only partly bend a mixed-production abatement portfolio, potentially ending with rates that advantage intensive production. A distinction in production methods would need to be considered across all *Codex* indicators not just nitrogen.

It is important to note that the economic optimum for nitrogen emissions reduction can be different to the biophysically and politically determined regional planetary boundary. The Paris Agreement translates into a threshold trajectory for greenhouse gas emissions based on a political and scientific consensus of the risks of warming achieving a sustained temperature anomaly above 1.5 degrees. Staying at 1.5 degrees was not chosen based upon economic optimality of greenhouse gas reduction.

The nitrogen emission thresholds set from biophysical criteria may be below or above economic targets emissions (Figure 4 middle panel). If they are too different, then from an economic point of view this introduces dead weight. Society is either not abating enough nitrogen pollution when it is cost-effective to do so ((a) in Figure 4 middle panel), or society is paying too much for further abatement ((b) in Figure 4 middle panel). However, from a political or biophysical perspective, the dead weight may represent intrinsic value, or other considerations not captured in the estimation of costs from impacts or the costs of abatement measures.

Simplification from emission targets to inputs or biophysical measurement

Table 2 (page 16) summarises the role of measurement along the impact chain of Figure 3. Any measurement concerning nitrogen impacts should be placed in the context of an impact chain and what the measurement is used for. Emission targets from either biophysical or economic criteria can translate into rates of nitrogen emission attached to commodities. Biophysical criteria, such as thresholds on pollution levels in waterways, can directly sponsor national regulatory action that aims to reduce emissions without emissions targets. Economic criteria also can be used directly to influence prices rather than to determine emission targets.

Emissions are closer to on-farm activity than biophysical impacts on natural and human capital. However, calculating emissions still requires monitoring proxies and toolsets for producers. NH_3, NO_x and NO_{3-} IPCC tier 1 calculations already exist for countries to calculate indirect N_2O for national commitments. If a trade or financial mechanism uses a principle of safe or target emission rates for commodities, then it is natural to consider if emission rates can be translated back closer to producer activity using fertiliser application and stocking rates. The translation is possible but is best used at a producer, local industry, or local government level. The flow from nitrogen inputs and use to nitrogen emissions (Figure 2) is highly specific to local conditions and current practices, including the quality of inputs. Using fertiliser and stocking thresholds at a national level for trade or other instruments would create administrative complexity and obscure the opportunity for nitrogen use efficiency. The thresholds would have to be updated more often as efficiency or the predominate type of fertiliser or feed in the market changes. As with the greenhouse gases CO_2 and CH_4, the emissions of NH_3, NO_x and N_2O represent a natural bottleneck in the impact pathway — coming from a multitude of economic activities and biophysical processes and going on to widely affect biophysical processes and then economic activities. Threshold measures for annual synthetic fertiliser application and manure rates for inputs are also weak proxies for nitrogen pollution and impacts. It could be counterproductive if users mistakenly associate high thresholds in efficient systems with higher impacts.

Thresholds for biophysical impacts are favourable to governments. Environmental monitoring of waterways and air pollution in cities already occurs, and they represent accumulation points in the impact pathways from diffuse emissions sources. Intermediate targets for harm to natural and human capital can only be conducted at the level of national monitoring (natural capital accounting). Government, through their non-financial capital accounting and assessment, can formulate policy responses.

Biophysical measurement is not the best option for private actors and markets however. Attributing thresholds on PM2.5 or nitrate in watersheds back to commodities or operations of private actors becomes difficult.

For parallels with greenhouse gas emissions, companies do not report their sea-level rise or other intermediatory climate metrics that are difficult to attribute. Multiple private initiatives track greenhouse gas emissions of agricultural producers and food companies and encourage voluntary reporting of GHG inventories across the now familiar Scope 1, 2 and 3 [153, 154]. It is not clear that private actors attempting to utilise and report biodiversity metrics is the best approach for biodiversity. Anthropogenic nitrogen and phosphorous losses from the agrifood system and land-use change are major causes of biodiversity loss [155]. Following GHG inventories it is more practical, and more effective from the viewpoint of being a step closer to business operations, for agrifood business to report nitrogen emissions and land-clearing, which result in biodiversity loss. Despite being one of the main causes of biodiversity loss and air pollution, as yet no major food company reports nitrogen emissions in their supply chains in a systematic way in sustainability reports similar to the scopes of GHG **(Figure 6, page 16)**.

Conclusion

Nitrogen losses to the environment are a key environmental impact from globally traded food commodities. *Codex Planetarius* intends that trade only be allowed below a benchmark for nitrogen surplus defined for a commodity and exporting country combination. However, determining what are "safe" levels of nitrogen surplus at a commodity level is challenging. Notwithstanding that safety needs to include sufficient nitrogen use to ensure food supply sufficiency and socio-economic development. An approach to performance standards for reactive nitrogen that could be similarly applied to other *Codex* indicators involves identifying a limit to total emissions and then allocations in that limit to commodities. Allocation is likely to be a strong point of contention for *Codex* to navigate.

To bridge the economic and biophysical domains, and the ability of public and private actors to engage in instruments, emissions limits (quantities) or social cost correction (prices) are recommended as the basis for performance standards. For setting total emissions limits for nitrogen, commensurability for the myriad of biodiversity and air pollution impact metrics needed across space and time make using contextual economic costs of impacts conceptually appealing, with the caveats on complexity of such calculations mentioned. At the other end, for simplicity, losing resolution in the different impacts among species and location and context of emission, life cycle analysis can calculate reactive nitrogen footprints of commodities (combined weight of nitrogen in all emissions for the commodity to reach export). ■

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Figures

Figure 1. Nitrogen flows through the agri-food system in 1961 and 2009. Figure from Lassaletta et al, Environ. Res. Lett. 11 (2016) 095007. TgN is one billion kilograms of nitrogen using the molecular weight of the nitrogen in compounds such as ammonia NH3. Flows to cropland, losses from cropland, and nitrogen embedded in international trade of crops, have increased 700% between 1961 and 2009, while cropland area has increased 20%. An estimated 26% of the nitrogen embedded in crops was internationally traded in 2009, with the bulk of traded crops used in livestock feed.

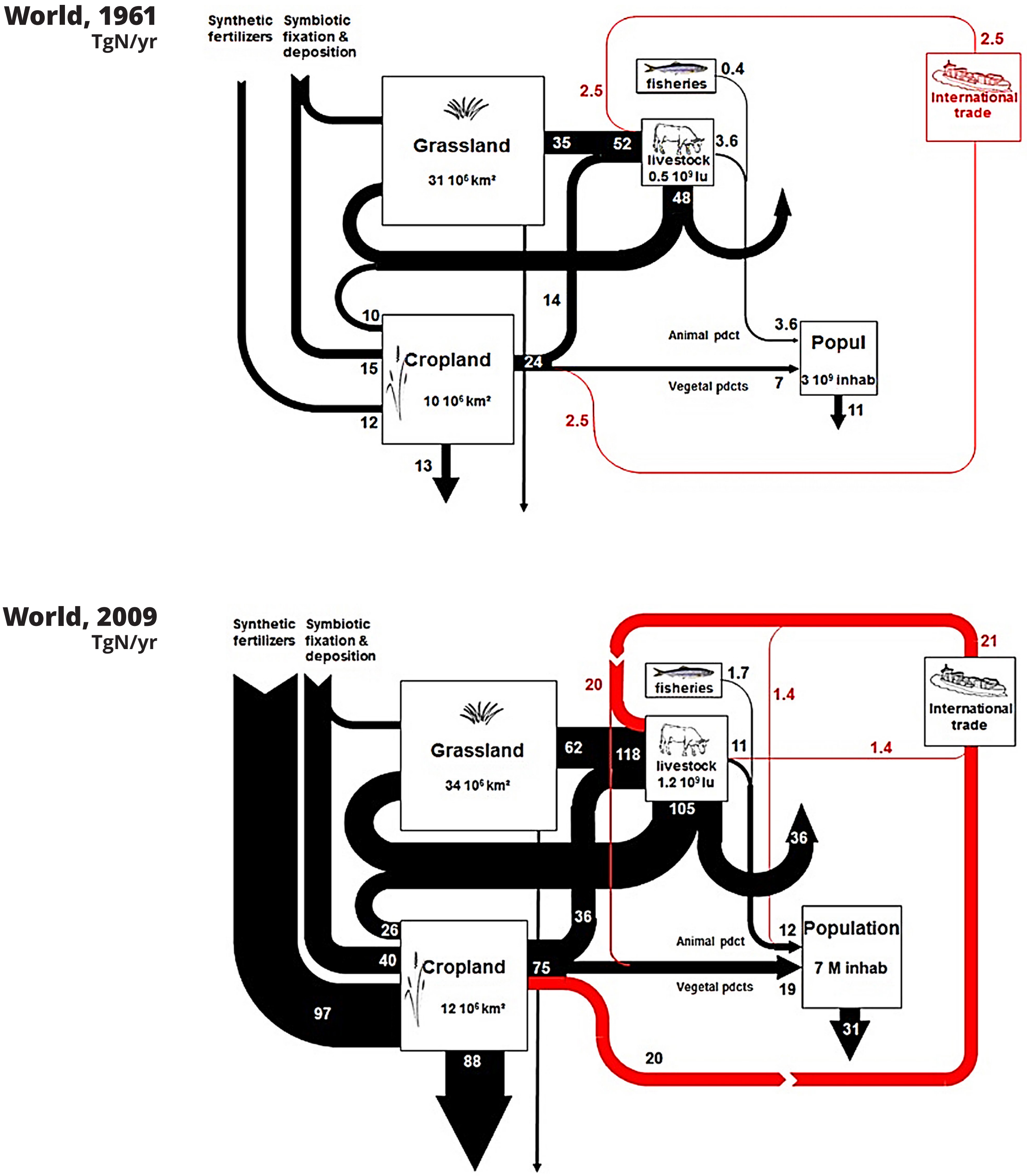


Figure 2. Pathway from reactive nitrogen (Nr) inputs to Nr emissions to air and water and to impacts. Direct emissions of the greenhouse gas N_2O result in future climate impacts, but N_2O and climate impacts represent a minor proportion of impacts from nitrogen emissions. Emissions of NH_3 and NO_x enter the biosphere primarily through volatilization of Nr from synthetic fertiliser application, recyled livestock manure as organic fertiliser, and livestock manure left on pasture. Chemical interactions of NH_3 and NO_x in the atmosphere create pollutants in the form of particulate matter and ambient ozone. A significant portion of the nitrogen originating in NH_3 and NO_x is deposited back on terrestrial ecosystems. Deposition creates additional biomass and carbon sequestration, but results in biodiversity loss and acidifaction. Due to the reactivity of terrestrial systems to available nitrogen, deposition can re-emit reactive nitrogen to the atmosphere in a serial process as part of the nitrogen cascade. This leads to secondary N_2O emissions and air pollutants. Most of the deposited nitrogen eventually ends up in waterways as nitrate run-off, joining direct nitrate run-off in causing imbalance in nitrification and deniftrication processes in aquatic ecosystems and impacts such as the "Dead Zone" in the Gulf of Mexico. Not depicted in the diagram are the timescales between emissions and impact. Direct exposure to air pollution from volatilization occurs in days, and deposition processes over weeks. Nitrate loads in aquatic ecosystems and soils accumulate over months and years, and seasonal loading and other environmental conditions such as temperature trigger eutrophication events. Nitrate loading in soils can take decades to emerge in surface water or reach deep groundwater sources. The delayed nitrate load in soils is believed to be reason why nitrate levels in European rivers have not decreased in proportion to reductions in nitrogen surpluses from fertiliser application and livestock manure. N_2O is inactive compared to NH_3, NO_x and NO_{3-}, and, on average, contributes to radiative forcing in the atmosphere for a century. The rate of reactive nitrogen input such as fertiliser application to emissions, also known as an emission factor, is highly local. Environmental conditions such as temperature, humidity, precipitation, soil type, crop type, type of fertiliser, livestock feed, and nitrogen managament practice can vary the emission factor considerably. For *Codex*, setting standards on nitrogen application as a proxy for emissions standards would be highly challenging and complex. *Author's elaboration.*

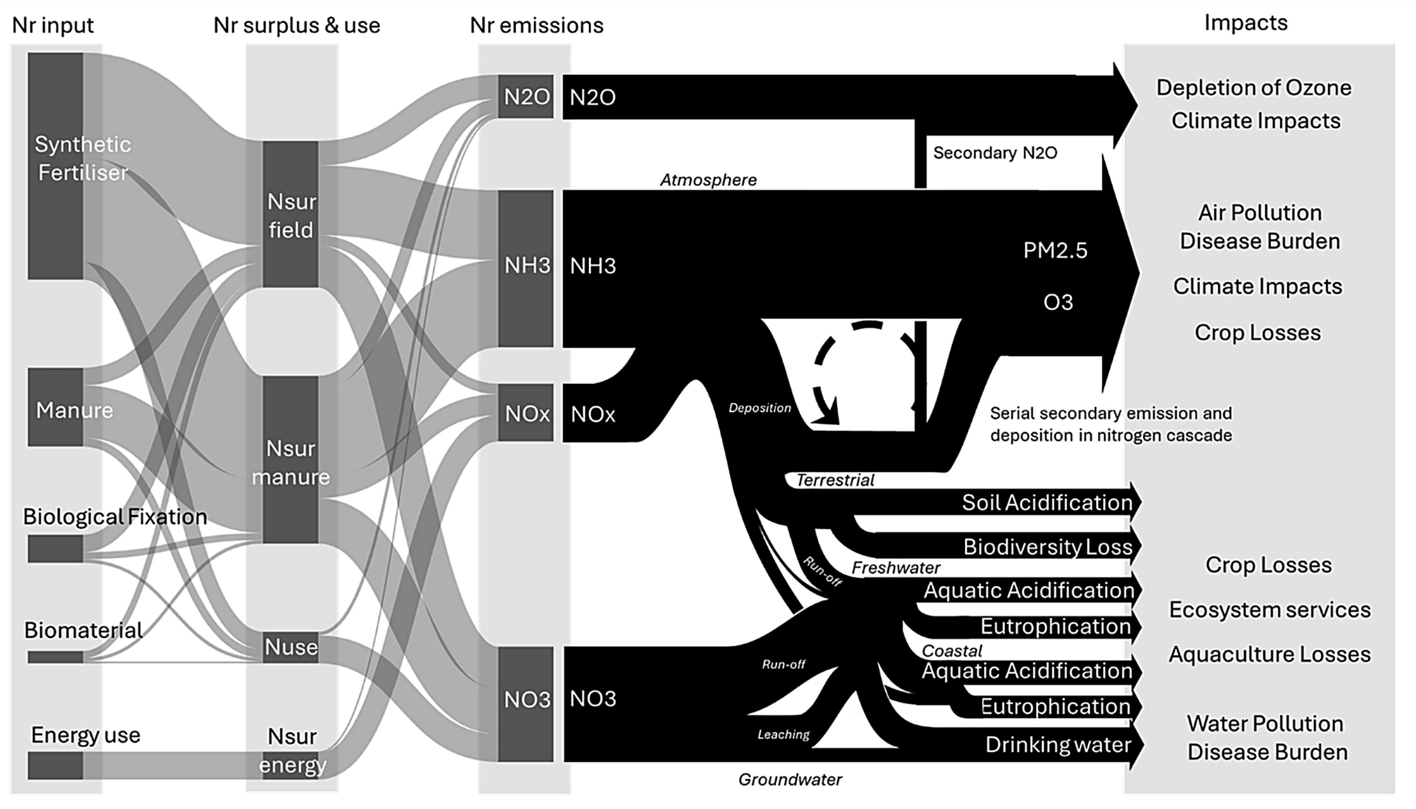


Figure 3. Environmental management and reporting tools compartmentalize impact pathways into: the activities and actors that create pollution, the pollution (output), the impact of the pollution, and the costs. Impact is a term usually reserved for present or future biophysical impact of that pollution on produced, natural, and human capital. Economies are underpinned by produced, natural, and human capital, and the impacts upon them translate into costs to present or future economies. In economic terms, the economic actors that produce the pollution are cost producers, and the economic actors impacted by future loss of human and natural capital are cost bearers. Cost bearers may be outside the value chain which benefited from the nitrogen pollution (externality), or be the beneficiaries in the value chain at a future time (internality). Conceptually, the activities in the food system, from production to consumption, are hugely dissagregated, diffuse, and heterogenous. The emissions themselves are also dissagregated and diffuse, but have the advantage of sharing chemical composition and commonality in biophysical pathways in air and water. Emissions have an advantage firstly of a natural chemical bottleneck for specification and secondly being more immediate to the polluting activities and actors than capital impacts and their economic costs. For nitrogen, the biophysical impacts are highly diffuse in both space and time, which again diffuse through multiple pathways to eventuate in cost bearing across future economies. Discounting and parity (measuring equivalency in costs across economies separated in time and space) are economic tools to turn costs into a present value so that cost-bearing of impacts and benefit receiving from producing impacts can be compared. This is advantageous for economic instruments designed to mitigate polluting activities or pay for adaptation. However, this economic bottleneck of present value has a different character than the chemical bottleneck at emissions. Uncertainty in economic conditions for cost bearers in the future, uncertainty in the costs that arise from natural and human capital impacts, and the many forms of economic equivalency one could choose create large uncertainty in present value. This possible cost bearing is a fitting representation of the highly complex and diffuse connection between cost producers and cost bearers mediated by the anthropogenic emission of reactive nitrogen. *Author's diagram.*

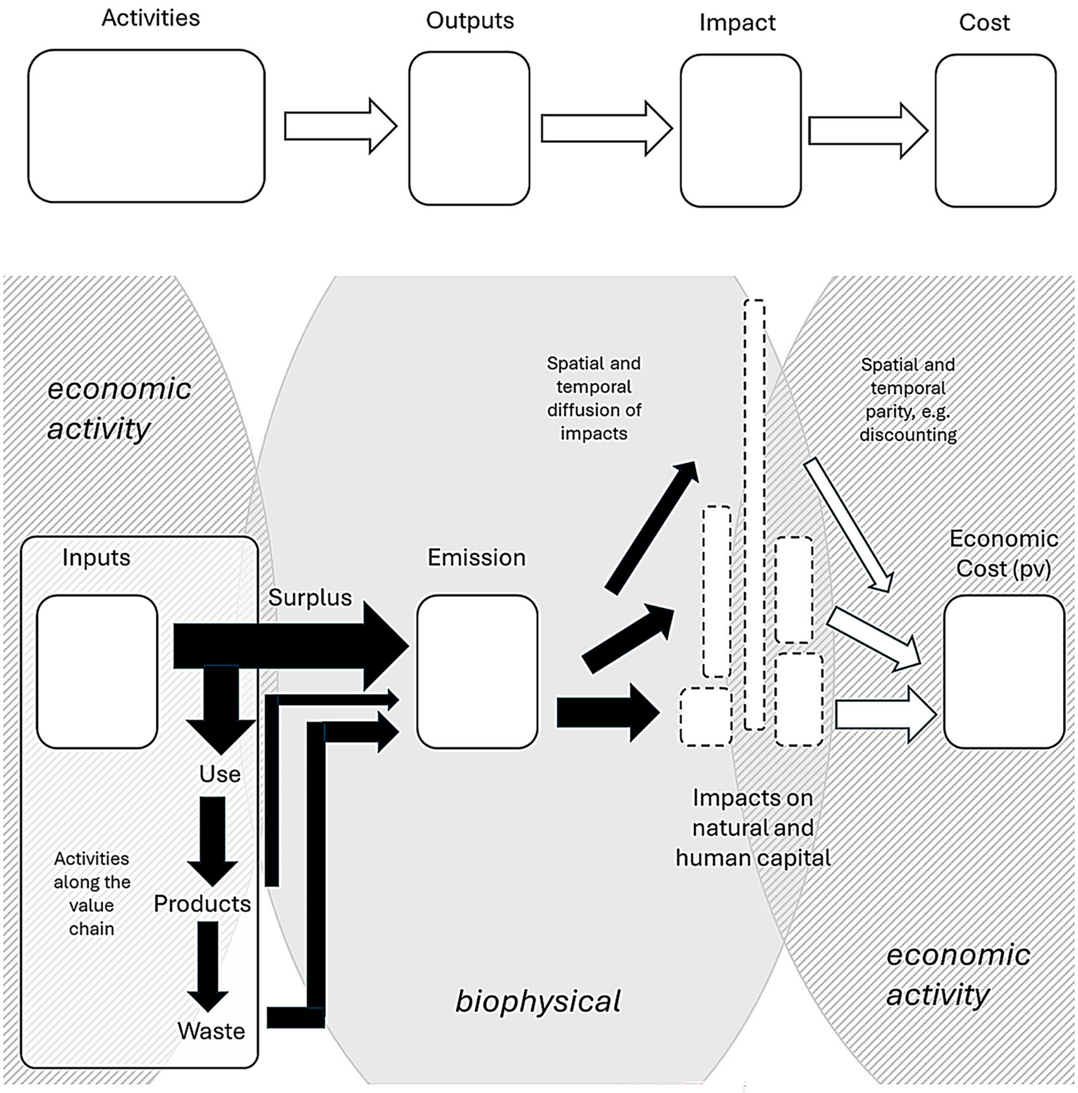
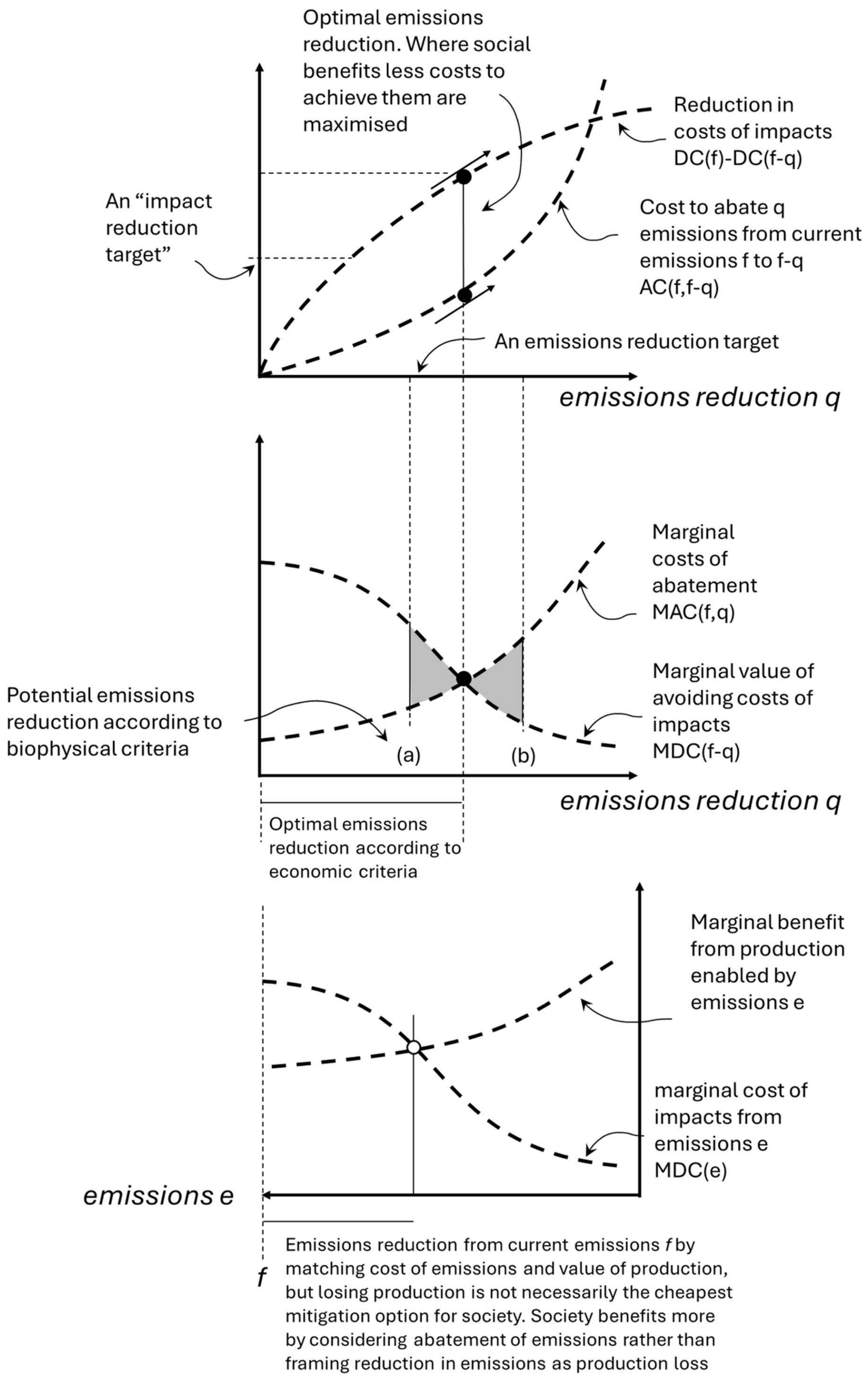


Figure 4. Optimal level of nitrogen emissions using the marginal value of abating nitrogen emissions and the marginal costs of abatement. Originating in Pigou's theory capturing externalities and internalities, the optimal level balances the risks in nitrogen pollution and the risks to food security and development, if they can be fully included in the knowledge about damages and abatement costs. An emission target not at the optimal level, that may be set by biophysical or political consideration, introduces economic deadweight (middle panel). Considering only production losses from reduced nitrogen application as the cost of abatement can also lead to a higher and non-optimal limit (bottom panel).



Emissions reduction from current emissions *f* by matching cost of emissions and value of production, but losing production is not necessarily the cheapest mitigation option for society. Society benefits more by considering abatement of emissions rather than framing reduction in emissions as production loss

Figure 5. Pigou's theory can also indicate contexts where nitrogen emissions should be higher than present to balance the risks of nitrogen pollution and the risks to food security and development.

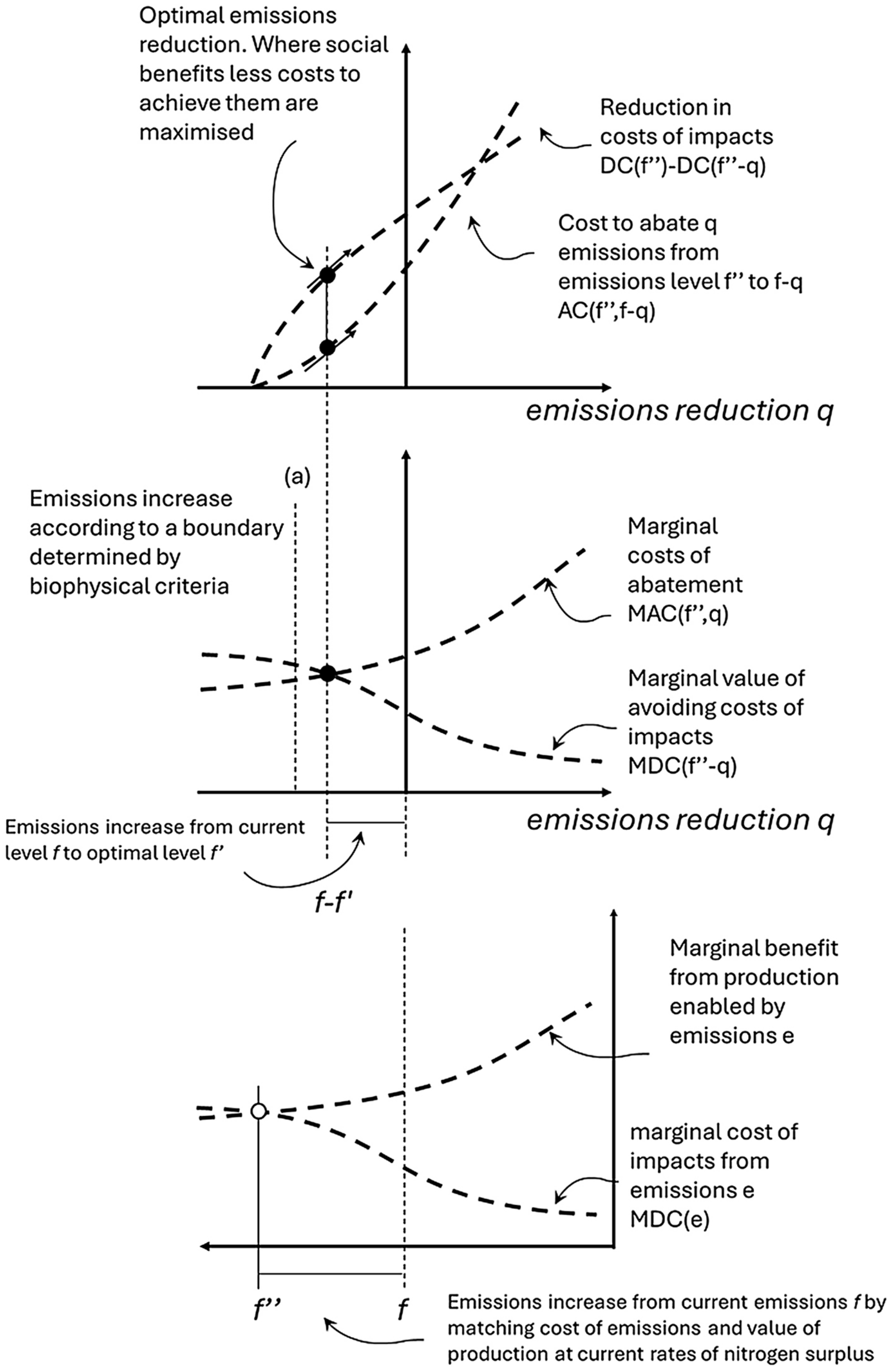
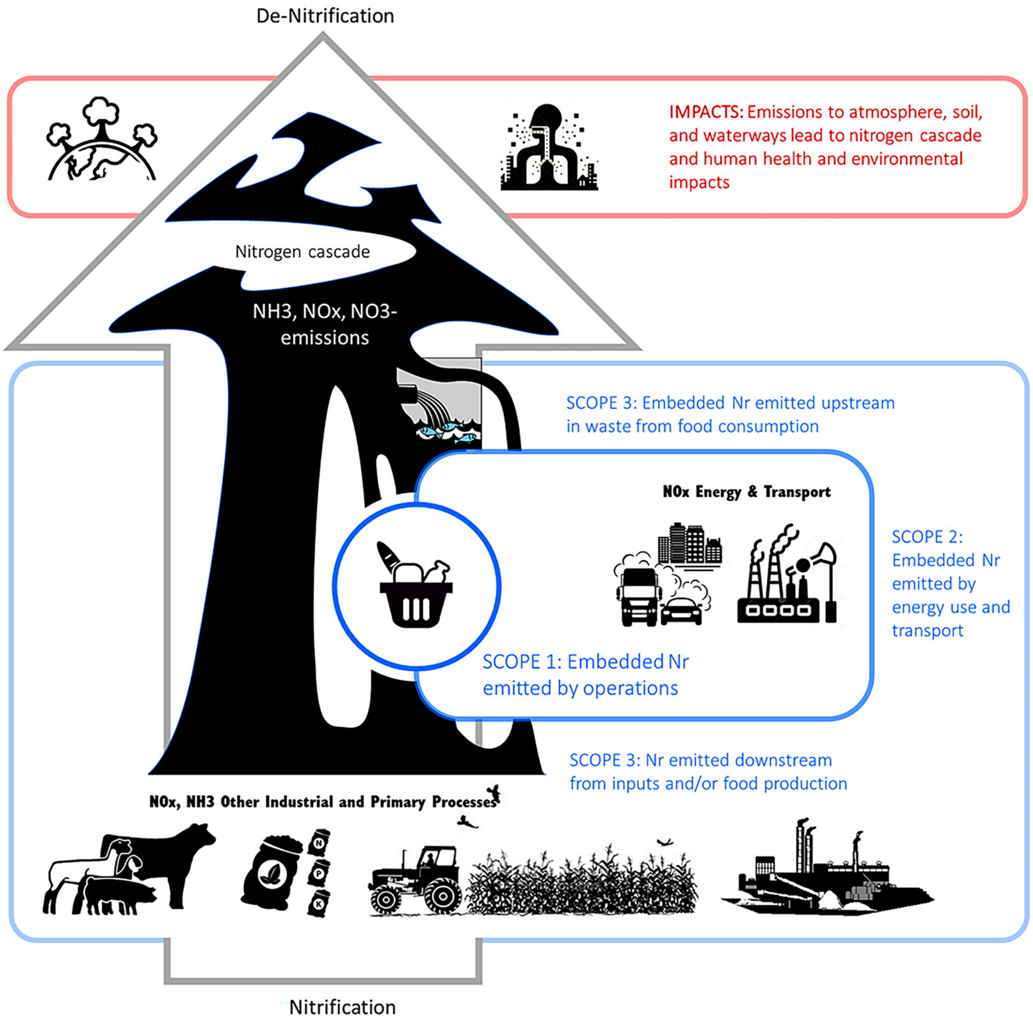


Figure 6. Nitrogen emissions outside of N2O can be framed in the familiar scopes of greenhouse gas emissions for corporate reporting. The bulk of emissions related to the agrifood system occur in food production and post-consumption human waste, while a minimal amount occurs directly in the operations of traders, food manufacturers, and retailers. The points of nitrogen emission in food value chain are inverted to where the benefits of emissions accrue. *Author's diagram.*



Tables

Table 1. Global shares of agrifood production nitrogen losses and macronutrient provision by dietary source. Losses in growing crops for livestock feed are counted within losses for meat and dairy foods. Losses from organic fertilisers obtained from livestock manure used to grow crops for direct human consumption are counted in vegetal foods.

Dietary source	Calorie share	Protein share	Share of nitrogen loss in production
Vegetal	82%	60%	35%
Livestock	17%	33%	62%
Fish	1%	7%	3%

Table 2. Summary of advantages and disadvantages for thresholds and measurement at the point of activity, emission, biophysical impact, or economic cost of impact.

Measurement point	Advantages	Disadvantages	Role in safe rates or performance standard
Synthetic fertiliser application and manure rates.	Easier for agricultural sectors. In many countries well tracked or approximated at national scale.	Poor proxy for impact. Discounts improvements in nitrogen use efficiency. Highly localised relationship to emissions.	Emission thresholds can be pulled back to application rates, but it requires inverting a second set of rates (emission factors). Thresholds for application rates complicated to set in international trade instruments. Thresholds for application rates required to be updated more regularly. Main role would be calculating emissions or combined N-footprints using application data and emission factors.
Emissions – losses of NH_3, NO_x, NO_{3-} and N_2O to the environment.	Tier 1 calculation for NH_3, NO_x, N_2O and NO_{3-} from production already exist IPCC. Chemical bottleneck between many processes producing the emissions and the many subsequent impact processes.	Prohibitively expensive to monitor directly. Depending on implementation could require monitoring proxies and toolsets for producers, especially NO_{3-} runoff. Currently tracked at aggregate levels or aggregate calculators (IPCC tier 1) using remote sensing or emission factors. Variable subsequent impacts from emissions due to local contexts. Allocation of emissions could be contested by competing interests.	Emission threshold by commodity and by country could be obtained by: 1. Thresholds for overall emissions set by biophysical concern or for balance of economic costs and benefits 2. Allocation links emission target to commodities 3. Allocated emissions divide by production volume yields rates Challenge with on-farm measurement to determine if a producer is within threshold. Likely to use application or stocking rates and emission factors to estimate.
Emissions – simpler N footprints. Inferred weight of nitrogen in all nitrogen losses to environment per unit of product.	Methods and metrics are available based on life cycle analysis. Start with a short-list of major commodities that contribute most to N losses. Software tools available that can calculate per unit of exported product.	Assumptions have to be made on allocation of N fertilizer and use. For livestock products, assumptions have to be made about the origin and cultivation of (sometimes imported) feed components. Loses resolution in the different impacts among species and location and context of emission. Based on studies. Coverage across countries has limitations.	Total threshold can become relative and percentage based. Such as targets to halve all reactive nitrogen losses. Relative allocation can be based on distributions of N footprint within the same commodity for country or region. A performance level in footprint could be chosen such that X% of the worst footprints are below the threshold. Easy incremental updating of this type of performance level. Challenge is that present data unlikely to differentiate and be able to produce a distribution of N footprints. Otherwise still requires an allocation method, for which species limits can be combined to form a performance level of N footprint.
Biophysical impact indicator. E.g. nitrogen loading in water catchment, PM2.5 pollution ppm, air pollution disease burden.	Preferred indicators to measure impact across time, space, and to whom the impacts occur. Multi-dimensional. Aggregates diffuse emissions sources, and monitoring largely exists already as part of national monitoring. Accepted by public and private actors.	Difficult to attribute to market actors and direct polluters. Issues of commensurability. Indicators dispersed in space and time – if aggregating by 'comparable value' it is preferable to use cost. Difficult to efficiently transfer to constraints or corrections on economic activities.	Used to consider the biophysical impact at risk by emissions, and thereby guide overall emissions targets. Implausible to use directly as commodity thresholds. Allocation to commodities problematic. Monitoring used to evidence the effect of instruments such as *Codex*.
Cost of impacts and optimal emissions.	Translates to corrections on current economic activities. Relatable to economic data and price instruments. Uses well-established economic principles for trade-off in costs, benefits, and comparing value across space and time.	Uncertainty in damage costs from emissions including representatives of valuation data (like WTP - typically based on surveys) and choices of discount rates. Requires complex models taking regional characteristics into account. Extensive data needed on abatement. Calculation of damages and abatement will be contested by competing interests.	Used to guide overall emission target. Benefit of avoided costs of pollution matched with the cost of abatement provides balance of risks of over-emitting or under-utilising nitrogen in an emissions target. Requires allocation to commodities, which can be based on cost-effectiveness.

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