Impact Report 2024

CLEAN AMMONIA:
THE DECARBONISED FUTURE OF FERTILISER

nium

About this study

This report was commissioned by We are Nium to Dr. Claudia Gasparovic. It is a result of a collaboration between both parties.

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We are Nium

Our **purpose** is a better planet for future generations. Our novel nanotechnologies give us the opportunity to decentralise and decarbonise global ammonia production. We call our system clean ammonia on demand.

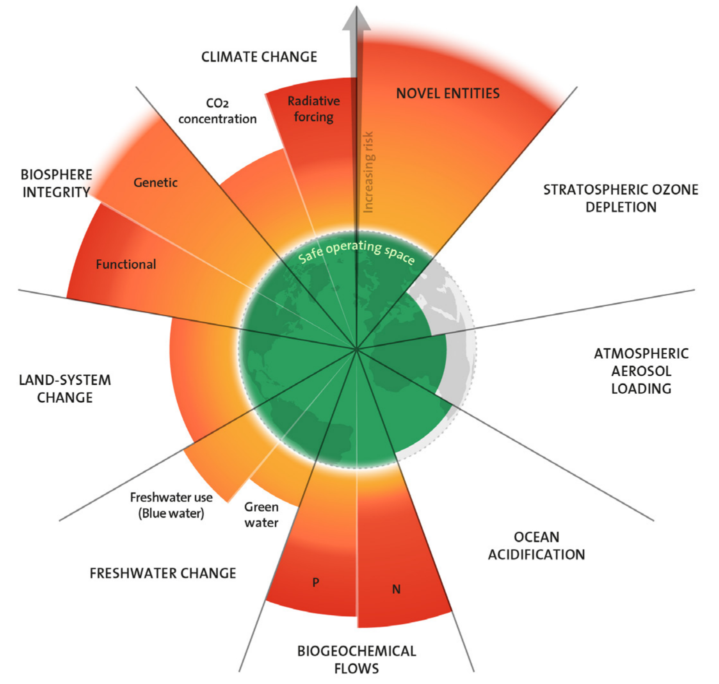
Nium's **mission** is to eliminate emissions. Replacing the current Haber-Bosch derived global ammonia market with Nium's cleaner alternative can eliminate 1-2% of global CO_2 emissions from agriculture, a further 3% from shipping and expedite the replacement of grey hydrogen with green hydrogen around the world. In terms of emissions reduction clean ammonia is an archimedes lever - a chance for massive impact at a critical time.

But it is not a silver bullet for all our environmental challenges. Emissions reduction, while urgent, is only part of the solution. What will clean ammonia on demand mean for the rest of our natural systems, our water, our air, our land?

In working to eliminate emissions we must take care not to burden shift, where impact on climate change is replaced with impact on other vital planetary systems.

In our quest to eliminate emissions how do we ensure that clean ammonia has the greatest positive impact in terms of food and fuel while we minimise negative impacts on the environment?

This impact report answers this question. We assess the current ammonia landscape and anticipate the impact of our technology across the 9 systems from Stockholm Resilience Centre's planetary boundaries framework.



Six of the nine planetary systems that sustain life have had their limits breached.

Credit: Azote for Stockholm Resilience Centre, Stockholm University. Based on Richardson et al. 2023, Steffen et al. 2015, and Rockström et al.

We begin with fertiliser

The mainstay of a $75bn and growing ammonia market

Ammonia fertilisers account for around half of global food. While the Ammonia market is projected to treble by 2050. But in terms of CO_2 emissions, ammonia production is already the most polluting chemical industrial process on our planet.

We look at the ways we can maximise clean ammonia's positive impact while mitigating risk and minimising harm. We chart the evolution of ammonia: from a polluting chemical today to driving tomorrow's sustainable food systems.

CLEAN AMMONIA: THE DECARBONISED FUTURE OF FERTILISER

What does it take to feed the world?

Plants are the basis of human nutrition. The main ingredients of photosynthetic life are well known: Sunlight. Water. Carbon. Nutrients.

As crops grow, they remove nutrients from the soil. Maintaining productivity requires replenishing the land [1], and, of all nutrients, nitrogen defines plant growth [2].

Nitrogen is the most abundant component of our atmosphere: 78% [3]. Unlike carbon dioxide, plants cannot absorb nitrogen in this gaseous, highly stable form (N2). They need reactive Nitrogen such as nitrous oxides.

For millennia we relied on nature's supply. Lightning would occasionally replenish Nitrogen directly from the air, some plants and fungi were able to synthesise ammonia too. As soils began to deplete we recycled nitrogen by applying manure, eventually importing nitrogen-rich guano to overfarmed lands.

But by the beginning of the 20th century demand was outstripping supply. Scientists realised we would need a step change from a hundred thousand to millions of tons of fixed nitrogen a year, in order to feed a rapidly growing population [4].

Anticipating this, in the early 1900s, a German chemist, Fritz Haber, created his own form of lightning, developing a technology that came to feed the world [3]. Haber designed an industrial catalyst that (under massive pressure and temperature) combined nitrogen from air with hydrogen - the first human synthesis of ammonia.

Haber's invention was the detonator to our 20th century population explosion. Taken to scale by Carl Bosch, Haber's innovation revolutionised agriculture allowing production of food at unprecedented rates. Scientists estimate that roughly half of global crop yields are made possible by Haber–Bosch nitrogen [3].

A century after Haber patented his discovery, we are totally dependent on the Haber-Bosch process for our food. Today, ammonia is the reason why half of us are here [3]. World demand for nitrogen as fertiliser has surpassed 100 million tonnes per year [5].

But our fixed nitrogen fairy-tale hides a dirty emissions secret. First, no more than 50% of nitrogen applied to soil is utilised by plants [6]: a large proportion is lost to the environment [3], with impacts on air, water and soil quality, and biodiversity [7]. Moreover, because the Haber-Bosch reaction can only happen at high temperatures and pressures, and the process is powered with fossil fuels, it accounts for almost 2% of global carbon dioxide emissions [8], about 450 million tons per year [9]. The transportation of ammonia also adds another 30 million tons of CO_2 emissions in the value chain [9].

Nium's patent pending nanotechnologies, housed in small scale reactors (the mighty minions) have the potential to eliminate the majority of emissions in production while mitigating environmental impacts in ammonia utilisation. Our proprietary catalyst technology makes ammonia possible at much milder conditions than the Haber-Bosch process, allowing for 'clean ammonia' to be synthesised 'on demand'. Green Hydrogen feedstock from water, nitrogen from air, ammonia synthesis powered by renewable energy.

Nium's nanotechnolgies change the $75 billion dollar ammonia market (projected to grow to $126 billion by 2030) in three ways:

1. Decentralisation

- Lower energetic costs. Our proprietary catalyst technology makes ammonia possible at much milder conditions than the Haber-Bosch process.
- The decoupling of ammonia production and fossil fuels.
- Local production of clean ammonia on demand.

2. Decarbonisation

- Elimination of grey/brown hydrogen in the ammonia production process.
- Recoupling with clean hydrogen at local sites, ammonia powered by renewables.
- Shorter supply chains and transport costs, less indiscriminate spreading of bulk delivered ammonia.
- More targeted 'just in time' application at point of production, less wastage and transport emissions.

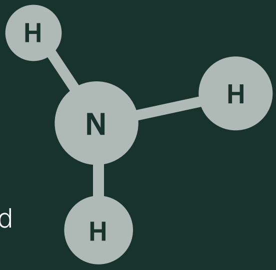
3. Democratisation

- More independence for fertiliser producers and farmers.
- Less reliance on global supply chains, middle men and poorly regulated foreign suppliers.

To understand our tiny solution to our massive fixed nitrogen problem we have to start small.

We begin by following the molecules...

The story of ammonia



The chemical formula for ammonia is NH_3. One Nitrogen molecule, fixed to three Hydrogen molecules. The nitrogen comes from the air but the hydrogen we use today is buried with the fossil fuels.

The story of ammonia begins deep underground. Hydrocarbons (natural gas, coal and oil) are dug up to feed the gas and energy demands of current ammonia production, totaling 2% of global energy demand [9].

About 40% goes to producing hydrogen, and the remainder is used to power the reaction combining this hydrogen with nitrogen from air to make ammonia. Powering the massive pressures and temperatures involved in the reforming and combustion process results in atmospheric CO_2.

Due to these massive energy demands, ammonia production is highly centralised, co-located at fossil fuel sites, despite farmers in rural areas being the main consumers [11]. Once hydrogen and nitrogen are combined, ammonia is safely stored and shipped or piped for long distances, 70% of it going either to farms or fertiliser plants, 10% being global exports [12]. Most of the ammonia produced worldwide is converted to urea (55%) and other fertilisers (such as ammonium nitrate, 11%, and calcium ammonium nitrate, 2%) before use [12].

Producing urea means first binding ammonia to carbon dioxide, which is sourced from more fossil fuels (usually from gas reforming). The reaction takes place in industrial facilities, and also requires great amounts of energy [1], demanding further fossil feedstocks.

The emissions from production and transport of ammonia and its derivatives such as urea contribute significantly to **Climate change**. While the additional CO_2 is temporarily sequestered in the urea and urea ammonium nitrate, all of it is later released when the fertiliser is applied to soil, in a total of 130MtCO_2/year.

Ammonia is a building block of our lives and the backbone of our food supply. But the carbon intensity of the process and a near total dependence on fossil fuels for synthesis and transportation is unsustainable and incompatible with the Paris Agreement goals or Net Zero by 2050 scenarios [12].

However, Carbon Dioxide is not the only negative impact of ammonia use in agriculture as we'll see by following the nitrogen molecules that reach the soil in fertiliser.

Nitrogen: the quick fix with a long tail

In general the current incentive structure in agriculture means we are applying more nitrogen to the soil than plants can absorb.

It is a problem of quantity and synchronisation. It is difficult to precisely supply enough nitrogen to meet crop physiological requirements [13]. Most products are spread directly on soil surface, with a high release rate, which means nutrients are immediately available. But due to run off, saturation and evaporation, plants are not capable of absorbing all the nutrients [14].

Overall, only about 50% of the nitrogen applied is absorbed by plants [15]. The remainder is lost by leaching to water bodies, volatilization to the atmosphere or soil erosion, in about equal proportions [16], and are transported to the Earth systems, suffering many chemical transformations along the way. These substances are drivers of change in the balance of planetary systems, making for a cascade of effects, where a single molecule can cause harm in different ways [17].

We can understand these impacts by looking at how Nitrogen lost to the atmosphere, water bodies and soil drive change in the planetary boundaries.

Atmosphere

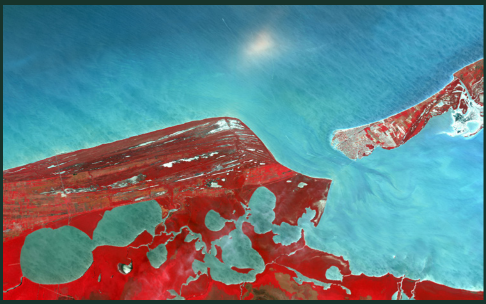
About 2.5% [18] of the nitrogen that is lost in soil is broken down by bacteria producing nitrous oxide (N_2O), a greenhouse gas 298 times more powerful than carbon dioxide [19] in causing **climate change**, with a lifetime of 116 years [20]. N_2O emissions from synthetic fertiliser use account for 56.6% of GHG emissions in the ammonia supply chain (about 662mi tCO_{2eq}) [9].

Along with other agricultural emissions, nitrous oxide also leads to crop yield reductions, requiring further agriculture expansion and affecting **land use change** [15].

Moreover, nitrous and nitric oxides (which are formed when N_2O reaches the stratosphere), are currently the most important **ozone-depleting** emissions, and are expected to remain throughout the 21st century [21].

Other forms of nitrogen that are lost to the atmosphere due to production and application of fertilisers such as ammonium, nitrate, organic nitrogen, etc. are significant contributors to **aerosol loading**.

Water



Half of NHx emissions end up deposited to the ocean, contributing to **ocean acidification** [22]. Fertiliser input to oceans is also the main driver of change in this boundary in estuarine and coastal regions [23].

On a global scale, the main culprit of ocean acidification is atmospheric CO_2, which dissolves in seawater making it increasingly more acidic.

About 2–10% of leftover N from fertilisers enter surface and groundwater, degrades water quality [14] and results in eutrophication [24], affecting the disponibility of **Freshwater**. The excess release of these reactive forms has long-term Earth system effects [25], significantly affecting global **Biogeochemical flows**.

Soil

While the excess nitrogen in soils disturbs **Biogeochemical flows**, the amount of fertilisers that was absorbed by plants makes them grow, causing indirect positive effects on carbon stored in soils, forests and grasslands either through increased productivity or avoided area expansion [26 & 27]. At a basic level ammonia significantly reduces the amount of land we need for agriculture.

This has a positive effect on **Climate change**. However, this relation is a complex one, because fertilisers also can negatively impact soil health, releasing carbon into the atmosphere [28].

Similarly, the increase in agricultural productivity means less **land** areas to produce the same output as organic systems (estimated by [29] as a 6% and 16-33% respectives increase in land demand from 2005-2050, or 55% and 71-81% considering effects of climate change). This also has positive repercussions for **biosphere integrity**.

Systemic effects

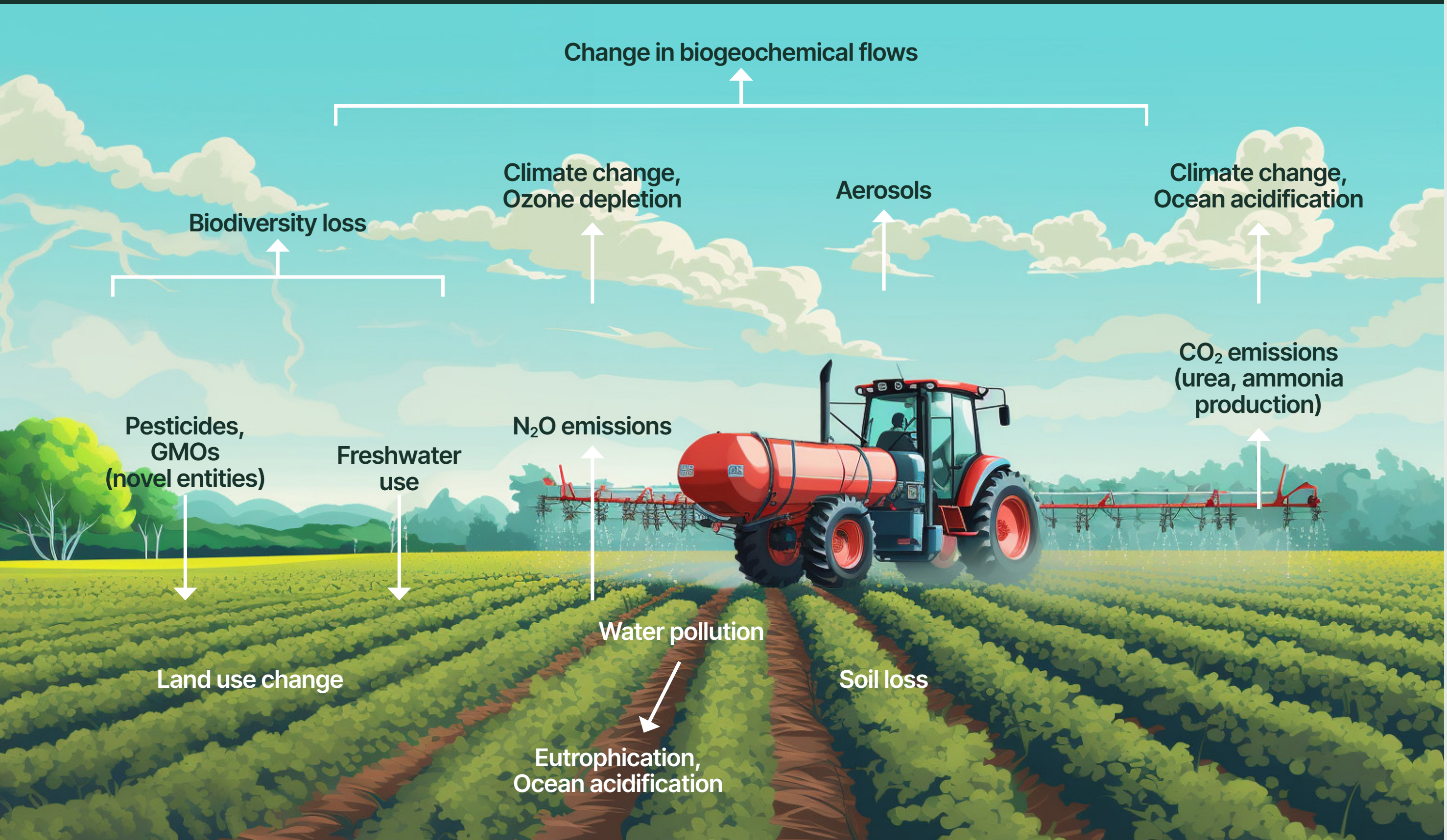
Some effects are also consequences of the interactions of these impacts and the broader systems they are inserted on.

The positive effect of fertilisers in reducing **land use** is uncertain and depends on enforcement of policies prohibiting or controlling deforestation when agriculture intensifies [26]. Moreover, croplands and pastures occupy ~40% of land surface [30] making agricultural production the planet's single most extensive form of land use [15].

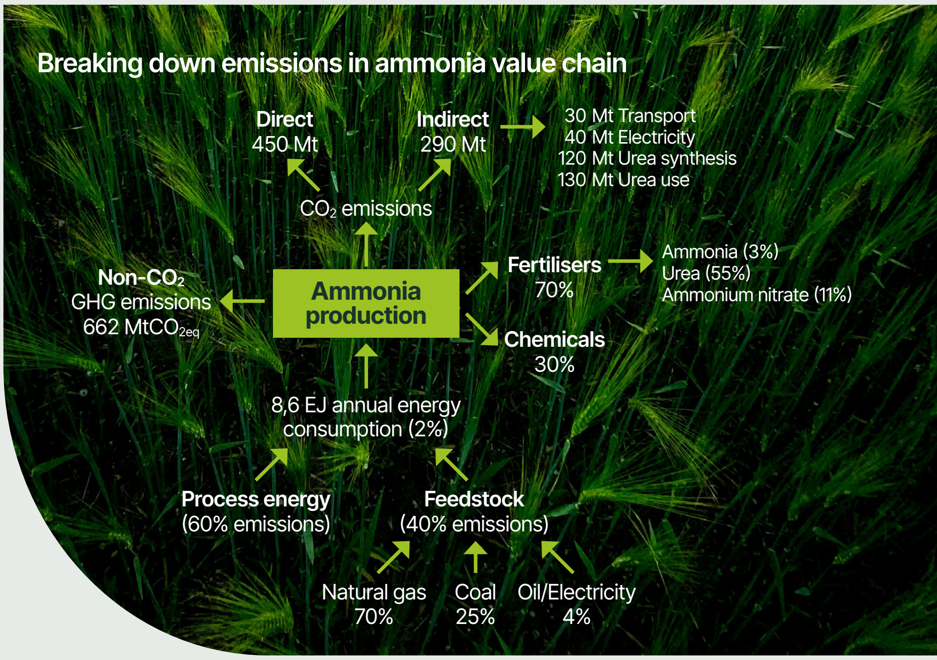
Land-use change from the expansion of agriculture is also the largest driver of **biodiversity loss** [31], together with intensive and monocultural practices and the introduction of **novel entities** such as pesticides, GMOs, modern seed varieties [32] and microplastics, majorly from organic and inorganic fertilisers [33]. This includes chronic fertilisation which is also one of the strongest drivers of species loss globally [33]. Nitrogen (N) deposition is projected as one of the three major pressures on biodiversity between 2000 and 2100 [34].

The direct impacts of Nium's minion reactor and the indirect impacts of the fertiliser value chain in the planetary boundaries are summarised below.

Risks associated with clean ammonia production will be presented in the following sections.



Breaking down the opportunities for emissions reductions in the fertiliser supply chain



Breaking down emissions in ammonia value chain

The emissions abatement potential of the minion depends on ammonia production and use pathways.

Replacing the Haber-Bosch process with our nano catalytic technologies allows us to change the hydrogen source from fossil fuels to water or biogas, and the fossil fuels used to power the reaction to renewables.

That means a carbon footprint per tonne of ammonia of 0.082 (wind, best available technology) to 1 tonsCO_2/ton NH_3 (solar), as opposed to the 1.6-3.8 tonsCO_2/tonNH_3 of the Haber-Bosch [36]. Only 1-2% of these emissions are from ammonia synthesis, as emissions from the minion are less than 3kg (solar) and less than 1kg (wind) per tonne of ammonia.

That would mean eliminating 40-95% of the total 315 MtCO_2/year direct process emissions, if green and blue hydrogen are used.

Decentralised, on demand ammonia production could also reduce transport emissions, about 30 MtCO_2/year. Eliminating long distance transport might also make the management of ammonia much easier, possibly displacing at least part of the urea value chain emissions (total of 250 Mt/CO_2 per year) [12]. This puts the maximum cap of possible emissions reductions from clean ammonia on demand in the fertiliser supply chain at the order of 300 MtCO_2/year (direct emissions) and further 320 MtCO_2/year (value chain), for current numbers only.

But ammonia demand is expected to grow. Under current trends, cumulative direct emissions from ammonia production would amount to around 28 Gt between now and 2100, or 6% of the emissions budget associated with limiting global warming to 1.5 °C in 2021 [12]. In keeping the same proportion destined for fertiliser use, that would mean 19.6 Gt of CO_2 emissions from the sector.

A market share of 3% by 2030 would mean reductions of 3.3-7 Mt/year under the IEA's Sustainable Development Scenario, and even higher for the Stated Policies scenario: 5.3-9.2 Mt/year, just for direct emissions from ammonia production for fertiliser.

Bottom up market and emissions reduction sizing in 2030 based in IEA scenarios

Each ton of ammonia

Eliminates 0.6-3.7 tons CO_2

Serviceable market emissions in 2030

3.3-9.2 MtCO_2 for 3% marketshare (4.2 MtNH_3)

Total market emissions in 2030*

248-320 MtCO_2 (138-140 MtNH_3 for fertiliser)

*Direct ammonia production emissions in the fertiliser market

Main risks and mitigation approaches

Reduce CO_2 and N_2O emissions
- Climate change
- Ocean acidification
- Ozone depletion

Reducer fertiliser loss/use
- Climate change
- Ocean Acidification
- Ozone depletion
- Biogeochemical flows
- Aerosol loading

Sustainable agriculture transition
- Climate change
- Ocean acidification
- Ozone depletion
- Biogeochemical flows
- Aerosol loading
- Novel entities
- Biosphere integrity
- Land use change

Reducing CO_2 emissions: The Elephant in the Room

Ammonia is a massive market projected to treble by 2050 [37]. But ammonia is built on the Haber-Bosch process and the Haber-Bosch process is built on burning fossil fuels.

Decentralised local facilities address energy security and supply chain issues in a market dominated by China and Russia and industrial incumbents. The 'on demand' nature means that the fertilisers are used sparingly when and where needed. By developing the clean ammonia market, and taking it to scale, we can reduce the reliance on centralised facilities, long supply chains and grey hydrogen. Clean ammonia on demand lets us eliminate emissions at source as we start from the roots up in the effort to decouple our food supply from fossil fuels.

The effect of deploying Nium's clean ammonia technology would be to reduce CO_2 emissions throughout the ammonia fertiliser supply chain: up to 620 $MtCO_{2eq}$/year for current numbers, and 19.6 $GtCO_{2eq}$ until 2100.

Reducing N_2O emissions: Salving the Sting in the Tail

Strategies include formulations with microbial inhibitors or slow release fertilisers; conservation tillage; control-release fertilisers; deep placement or smaller, split applications during the growing season [13 & 38]; and choosing the right fertiliser for each situation. **Strategies such as these, along with wider changes in the agri-food system, could reduce fertiliser emissions by 70%** [39]**.**

Reducing fertiliser loss or use: Efficiency as an Impact Tool

Besides the practices above, other solutions are "low tech" tools for site specific nitrogen management; integrated nitrogen management combining chemical fertilisers with indigenous sources of N; green manuring by using legume crops which fix atmospheric N in the soil; conservation management; proper crop rotations; genetic improvement and precision farming [38 & 13].

The principles of adequate matching of soil needs and nutrient input for greater fertiliser efficiency are summarised by the 4R nutrient stewardship management practice: **right source, right rate, right time, right place.** The source of nutrients is an important lever. While in general, solid urea loses more nitrogen as a pollutant than ammonium nitrate, these losses are mostly as ammonia, while the latter are in the form of nitrate and nitrous oxide [40]. Either can lead to more N_2O emissions, depending on type of soil - under dry conditions, nitrate-based fertilisers can result in lower emissions than urea [41,42].

No-till agricultural system

Researchers from China Agricultural University, Stanford University and other leading institutions reported effective engagement, over a decade, of millions of small Chinese farmers to adopt enhanced management practices, leading to 10% increased yields with 14.7–18.1% reduction of nitrogen fertiliser application, 15% less nitrogen losses and 15-25% reduction in GHG emissions [43]**.**

Sustainable agriculture transition: A collaborative approach

Current food systems present a challenge: promoting food security and achieving the Zero Hunger Sustainable Development Goal, while reducing impact on planetary systems [44]. Solving this conflict between nutritional goals and environmental sustainability demands urgent innovation and open thinking to redesign agriculture [13].

A sustainable agriculture transition is needed. Some pillars of this transformation [45] have been mentioned, such as minimal tillage and diversity in cultures. Others include integrated systems of crops with livestock and trees, such as agroforestry, expanding regenerative agricultural systems, avoiding pesticides, promoting research through farmer networks and overall taking into account externalities of food systems.

Moreover, achieving nutritional goals is expected to become increasingly more challenging with climate change and increasing prevalence of carbon taxes such as the Cross-Border Adjustment Mechanism (CBAM) to expedite the energy transition, considering increasing costs of fossil fuel extraction, carbon taxes and the resulting fall in cost-effectiveness of the highly fossil dependent ammonia supply [46].

Decarbonising the fertiliser sector, increasing fertiliser efficiency and reducing nitrogen inputs are important pieces of this puzzle - tricky ones, because of how much the food system depends on synthetic fertilisers. There is also a consideration of environmental justice to be made: countries differ in the use of their fair share of global nutrient activation [47], and these differences relate to historical global inequities in the access to nutrients. Food security within the safe boundaries also requires global redistribution of nutrients and of rights to use nutrients [48].

Agroforestry system in the Brazilian Amazon

But it is also important to understand these solutions in the context of food systems and dietary habits. Reducing food waste and dietary shifts to reduce demand for animal products have been judged paramount to achieve deep nitrogen reduction targets [49]. A study found that when combined with these measures, a partial (e.g. 40%), and for certain cases even a full conversion to organic production becomes viable, with land use below the reference scenario, even while considering medium effects of climate change [29].

Combining all these strategies together means not having to implement a single measure at maximal coverage, while still increasing the sustainability of the global food system [29].

Clean ammonia is arguably our most powerful tool, an archimedes lever in terms of agricultural emissions reduction, but it is **only one tool in a broader climate and biodiversity action toolkit**. Innovation and collaboration with positive actors across the whole food system is how we pave a way forward to regenerative food production and practices.

Protecting terrestrial and aquatic ecosystems in Europe requires reducing N inputs in 31% and 43%, respectively, higher numbers than the 20% reduction goal for fertiliser use in the 'Farm to Fork' strategy (FFS) of the European Green Deal [50].

Opportunities for social and nature-positive impacts

Nium exists to eliminate emissions. But our potential for positive sustainable transformation goes beyond carbon. Our purpose is a better planet for future generations and this is a critical hour for action.

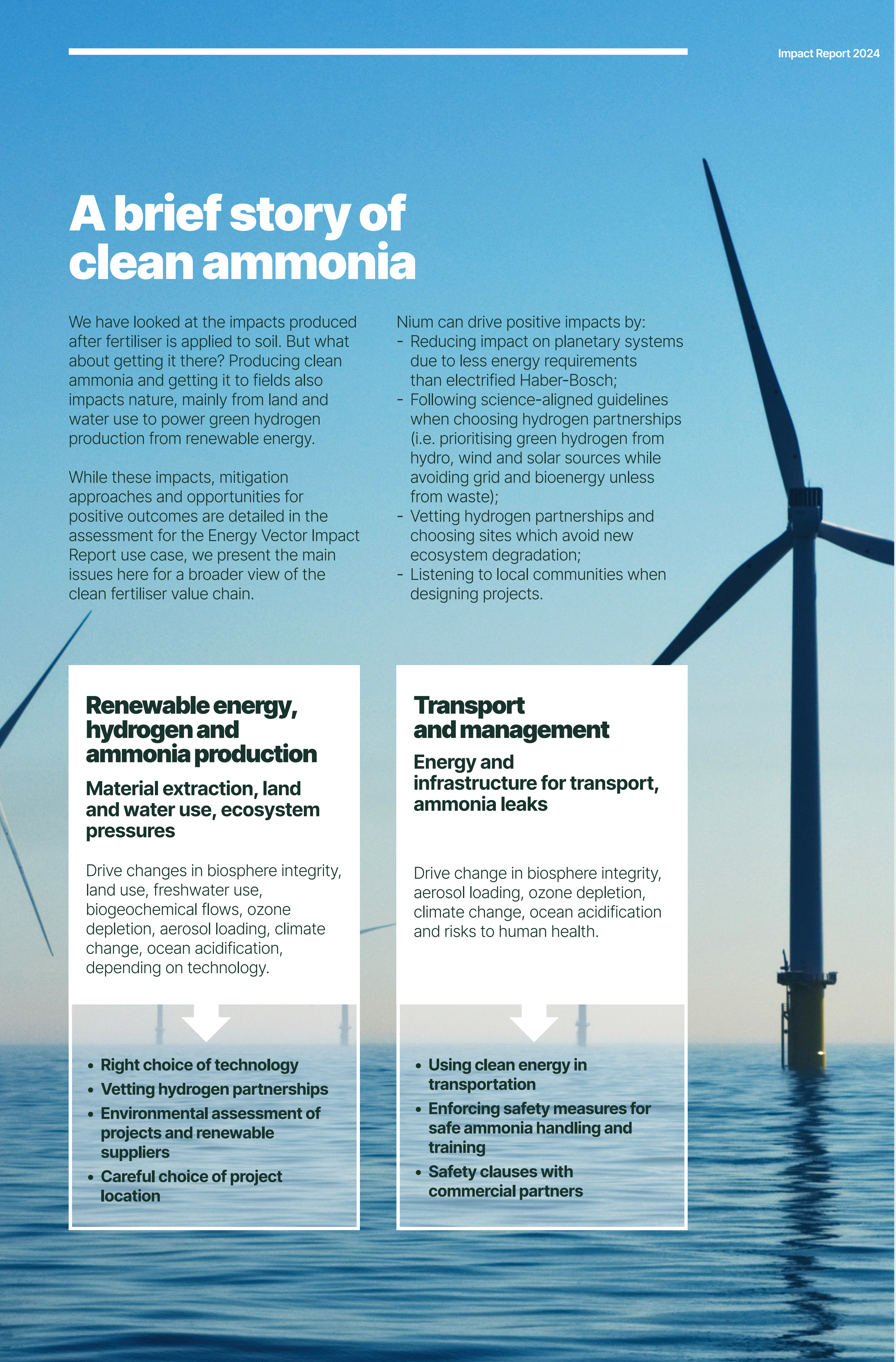
Maximising emissions benefits and minimising negative impacts are central to our thinking.

In our theory of change, a new nanotechnological paradigm is an opportunity to change the system.

Changing the system will take time, and will require bridging the old and the new.

The ways the technology is deployed can contribute to a sustainable agricultural transition, as the following illustration shows.

1. **Eliminating CO2 emissions by decarbonising and decentralising ammonia-based fertiliser production, and displacing urea fertilisers.**
2. **Deployment associated with knowledge transfer and technologies promoting improved fertiliser efficiency and less nitrogen input.**
3. **Deployment associated with knowledge transfer and technologies promoting sustainable land stewardship, like regenerative agriculture and agroforestry.**
4. **Promotion of research in association with universities and farmers.**
5. **Prioritised deployment in degraded land for restoration and later transformation in regenerative management properties.**
6. **Strict vetting policies for buyers, preventing use in areas from deforestation.**
7. **Listening to and incorporating traditional knowledge of sustainable resource management, especially from indigenous peoples.**
8. **Sustainable use of biomass with crop and livestock association models; producing hydrogen from gasification of biowaste.**
9. **Contributing to food security and equality in nutrient access by decentralised production.**
10. **Showing leadership to incentivize changes in the sector.**



A brief story of clean ammonia

We have looked at the impacts produced after fertiliser is applied to soil. But what about getting it there? Producing clean ammonia and getting it to fields also impacts nature, mainly from land and water use to power green hydrogen production from renewable energy.

While these impacts, mitigation approaches and opportunities for positive outcomes are detailed in the assessment for the Energy Vector Impact Report use case, we present the main issues here for a broader view of the clean fertiliser value chain.

Nium can drive positive impacts by:

- Reducing impact on planetary systems due to less energy requirements than electrified Haber-Bosch;
- Following science-aligned guidelines when choosing hydrogen partnerships (i.e. prioritising green hydrogen from hydro, wind and solar sources while avoiding grid and bioenergy unless from waste);
- Vetting hydrogen partnerships and choosing sites which avoid new ecosystem degradation;
- Listening to local communities when designing projects.

Renewable energy, hydrogen and ammonia production

Material extraction, land and water use, ecosystem pressures

Drive changes in biosphere integrity, land use, freshwater use, biogeochemical flows, ozone depletion, aerosol loading, climate change, ocean acidification, depending on technology.

- **Right choice of technology**
- **Vetting hydrogen partnerships**
- **Environmental assessment of projects and renewable suppliers**
- **Careful choice of project location**

Transport and management

Energy and infrastructure for transport, ammonia leaks

Drive change in biosphere integrity, aerosol loading, ozone depletion, climate change, ocean acidification and risks to human health.

- **Using clean energy in transportation**
- **Enforcing safety measures for safe ammonia handling and training**
- **Safety clauses with commercial partners**

Clean ammonia: systemic view of a super-leverage point

Nium can act in different sectors of the economy: fertiliser, fuel, energy, chemicals. But they don't exist in isolation from each other. Zero-emissions solutions like the mighty minion can influence multiple sectors at once.

In fact, a recent report [51] identifies Ammonia as one of three *"super-leverage points"* that *"could trigger a cascade of tipping points for zero-carbon solutions in sectors covering 70% of global greenhouse gas emissions"*. A clean ammonia tipping point in fertiliser could reduce green hydrogen prices, in turn helping unlock tipping points on clean ammonia use for shipping and steel production.

Many other opportunities for synergic cross-sector clean ammonia deployment are identified in the figure below. By working across sectors and with a systemic view, Nium's solution can be made more powerful, helping unlock the path to a carbonless and sustainable economy.

We are Nium. We don't pick teams. We are not politicians. Or advocates for shipping fuel. Or paid lobbyists for the hydrogen economy. We are not a fossil fuel company or a chemical company or an energy company or a shipping company. We are a climate company.

We're nanoscientists, entrepreneurs and engineers with a mission to eliminate massive emissions. Our nanocatalyst in small, modular reactors is a disruptive technology that could trigger these global, systems-wide tipping points. Our approach to sustainability is the same:

> ***We're catalysts for change; driving big impacts from small things.***

What we're thinking about

Nium is situated at the intersection of complex, interconnected systems and industries. This document reflects our efforts to assess the impact of Nium's nanotechnologies on Ammonia production, showing our commitment to a broader view of the climate and ecological crisis.

As we develop as a business and as an industry, we will need to address more issues, such as:

- Implications for other nutrients frequently delivered with N, such as P and K
- Avoiding perverse incentives for more fertiliser use with a distributed production and local sales business model
- Avoiding reducing resilience of food systems by tying them more closely to the energy sector with hydrogen
- Providing fertilisers while increasing resilience of food systems, lessening its reliance on external fertilisers
- Avoiding biosourced hydrogen being a risk to food security by competing for land
- Impacts for other industries, especially in the chemical sector (i.e. steel, explosives, use as weapons)
- Avoiding perpetuation of colonial paradigms when sourcing energy from the global South
- The impact on social systems and foundations, not being the focus of this report, have only been cursorily studied.
- This report presented a first map of possible impacts on natural systems, as proxied by the planetary boundaries framework, based on value chain mapping and secondary literature research. We use this framework while recognizing that impact assessment for actual deployment will need to consider local conditions and management approaches, as well as data such as a LCA assessment of Nium's technology.

Key takeaways

1. Ammonia is a backbone of **global food systems**, and the most **CO$_2$-emitting** chemical industrial process on the planet.

2. **Clean Ammonia** is expected to play an essential role in global **decarbonisation**.

3. **Nium's** patent pending **nanotechnologies**, housed in small scale reactors (the mighty minions), allow **'clean ammonia'** to be synthesised **'on demand'**.

4. Clean ammonia on demand has the potential to eliminate up to **300 MtCO$_{2eq}$** from ammonia production and **320 MtCO$_{2eq}$** in the value chain now - **19.6 Gt** by 2100.

5. With **5-8 Mt** of ammonia on the fertiliser market (3-6% market share), Nium would reach its goal of eliminating **10 MtCO$_{2eq}$** by 2030. That's the reason why we exist: to **eliminate emissions**.

6. But in addressing the climate crisis, we must not incur in **burden-shifting**, where impact on climate change is replaced with impact on other **vital planetary systems**.

7. We look at impacts of the clean ammonia value chain for three reasons:

   Mission: To ensure we have the right baselines, and to potentialize our impact on eliminating emissions.

   Business strategy: With growing awareness of broader environmental impacts by investors and regulators, we want to be ahead of the game while promoting co-benefits like better yields.

   Purpose: Maximising positive impact in our value chain, we help secure a better planet for future generations.

8. Impacts of our value chain (due to renewable energy, hydrogen production, nutrient loss and conventional agriculture) demand that we make **informed choices**, **listen to science** and to **local communities**. To deploy our technology driving broader positive change, we need **infinite invention** - from Nium and our partners.

9. Nium is well-situated to drive positive change because:
   - We're decarbonising essential sectors in the economy.
   - Our flexibility allows us to grow sustainably in different markets.
   - We can act as a bridge between them to drive positive change synergically.
   - We're helping align them with a **decarbonised**, **decentralised**, and **democratised** future.

10. Our sustainability strategy is simple: **We're catalysts for change**.
    In our theory of change, a new nanotechnological paradigm is an opportunity to change the system. We do it by having a systemic view and working synergically across sectors, bridging the old and the new, and having a vision of a better future.

Annex I - Literature review of impacts of Nium's technology and fertiliser supply chain on planetary boundaries

Climate change

Direct positive impact: Switching the current Haber-Bosch ammonia production system for the minion reactor prevents further increase of CO_2 concentration. In a rough estimate, considering that 1 ppm by volume of atmospheric CO_2 corresponds to 2.13 Gt of carbon [52] and that natural sinks absorb about 55% of anthropogenic emissions, the 315 $MtCO_2$ from ammonia production for fertiliser mean about 0.02ppm of increase per year, or 0.029% of the excess CO_2. The positive impact is even greater if displacement of the urea value chain is considered.

Indirect negative impact: The role of N_2O emissions from fertiliser use in radiative forcing from 1750-2019 is estimated as 0.21 ± 0.03 W $m^{-}2$ [53], which represented 6% of total anthropogenic radiative forcing by 2009 [18] and 10% of the excess planetary boundary value for this control variable. N_2O emissions from anhydrous ammonia could be greater than those from urea [54,55]. Other impacts on soil sequestration are difficult to quantify.

Ocean Acidification

Indirect positive impact: Associated with reducing CO_2 emissions in the ammonia supply chain.

Indirect negative impact: Nutrient inputs from fertilisers to the seas and oceans are estimated to cause 10–50% or more of the anthropogenic CO_2-driven changes near the major source regions and in marginal seas [22].

Stratospheric ozone depletion

Indirect negative impact: Fertiliser and manure use is the main anthropogenic source of nitrous oxides [15] (3.9–5.3 TgN/year in 2010), which caused the majority of the increase in N_2O emissions since the industrial era [56] and are estimated to account for 42% of ozone-depleting potential weighted emissions [21].

Freshwater change

Direct negative impact: Current ammonia production is highly water intensive, requiring 3-5 tons of water per tonne of ammonia [57]. Impacts on water use of ammonia production depend on the technology, being higher for biomass-sourced than for green hydrogen [58], but both are expected to be higher than Haber-Bosch. While in HB water contributes to half of hydrogen from syngas, it provides 100% of the hydrogen for electrolysis.

Indirect positive impact: Reducing consumption of the 12.8 m^3/ton of urea production [59].

Indirect negative impact: Agriculture accounts for ~70% of global freshwater withdrawals, and agriculture's role in the status of this PB is estimated at the 84% level [15].

Atmospheric aerosol loading

Indirect negative impact: In many densely populated areas, aerosols formed from fertiliser application and animal husbandry dominate over the combined contributions from all other anthropogenic pollution [60]. Estimates indicate that global NH_3 emissions from N fertilizer use have increased from 1.9 ± 0.03 to 16.7 ± 0.5 Tg N/year between 1961 and 2010 [61].

Novel entities

Indirect negative impact: The boundary states a limit of 0% introduction of untested novel entities. At least 105 chemical pesticides were launched or under development from 2010-2020[62], and Stehle and Schulz (2015) report that the concentrations of 50% of the insecticides detected exceeded regulatory thresholds [15]. Fertiliser use is a major source of microplastics in soil [33].

Land system change

Direct negative impact: Land use for deployment if associated with deforestation in agricultural areas.

Indirect negative impact: Land for renewable energy and agriculture.

Earlier studies have shown that, in tropical and subtropical countries, agricultural expansion accounts for 73% of deforestation [63]. Kissinger et al. (2012) and Hosonuma et al. (2012), using FAO data, estimate that agriculture is the driver for around 80% of deforestation worldwide in the period 2000–2010 [15]. Indirect positive impact: A modeling study estimated 8–15% higher values of deforestation for 100% organic in comparison to the reference system in 2050 [29].

Biosphere integrity

Indirect negative impact: Land-use change from the expansion of agriculture is estimated to drive 80% of changes in biosphere integrity [15]. It is estimated that NH_3 and NOx emissions have reduced forest biodiversity by more than 10% over two-thirds of Europe [64] Renewable energy production can impact ecosystems and wildlife.

Biogeochemical flows

Indirect negative impact: Fertiliser use is the main source of excess nitrogen in planetary systems. The 50 Tg of applied N fertilizer [13] lost to the environment represent 40% of the excess over the planetary boundary.

Opportunities

Opportunity	System	Impact	Assumptions	Considerations	Further Reading	Planetary Boundary
Reduction in Scope 1 emissions	Atmosphere	**Market** 126-283 MtCO$_2$e (2021) 28 Gt until 2100 **Nium** For a market share of 3% in 2030, 3.3-9.2 MtCO$_2$/year	**Market** 315 MtCO$_2$e of Scope 1 fertiliser emissions. **Nium** Based on IEA's Stated Policies and Sustainable Development Scenarios, considering a mix 10/20/70 of small/medium/large Nium plants. Carbon footprints: 0.082 (wind, best available technology) to 1 tonsCO$_2$/tonNH$_3$ (solar), 1.6-3.8 tonsCO$_2$/tonNH$_3$ (Haber-Bosch) [36].	Emissions abatement potential of the minion depends on ammonia production and use pathways. Different future scenarios imply different baselines and potential for emissions reductions.	[12], [36]	Climate change
Reduction in Scope 2 emissions	Atmosphere	Up to 40 MtCO$_2$/year	By eliminating HB's electricity needs and facilitating transition to renewable electricity.	Values are for 2021; future baselines could vary.	[12]	Climate change
Reduction in Land Use and deforestation due to increase in productivity	Biosphere	Land demand increase from 2005-2050 of 6% vs 16-33% for organic farming, or 55% vs 71-81% considering effects of climate change. For deforestation, 8–15% increase for 100% organic in comparison to the reference system in 2050.	Global estimates based on a food systems model. Reference scenario for 2050 employs FAO forecast's assumptions. Full assumptions can be consulted in the original paper.	This effect is uncertain and depends on enforcement of policies prohibiting or controlling deforestation when agriculture intensifies [26].	[29]	Land system change
Reducing transportation in supply chains and transport emissions	Atmosphere	30 MtCO$_2$/year	Decentralised ammonia production requiring less transport.	Values are for 2021; future baselines could vary. Part of clean ammonia production can be centralised close to renewable sources. Infrastructure and materials such as hydrogen also require transport.	[12]	Climate change
Reduction in Scope 3 emissions by displacing urea value chain	Atmosphere	Up to 250 Mt/CO$_2$ per year	Decentralised ammonia production can lead to direct use of anhydrous ammonia instead of derivatives such as ammonia. Replacement only occurs if baseline emissions remain the same or are lower.	Though anhydrous ammonia is used in large proportions in places like the USA, it is not apt for any soil and climate, and requires safety measures due to ammonia's toxicity.	[12]	Climate change
Reduction in Scope 3 emissions and nitrogen loss by associating deployment with mitigation measures	Atmosphere	**Market** Up to 70% emissions reductions in a global scenario **Nium** Up to 15.96 Mt for 3% market share in 2030	**Market** Expectation for deployment of technologies such as microbial inhibitors and targeted applications associated with wider changes in the agri-food system. Full assumptions can be consulted in the original paper. **Nium** Baseline emissions based on IEA's Stated Policies scenarios (2021). Considers deployment of various mitigation strategies in 90% of operations.	Reduction potential for each technology varies depending on soil and climate. These measures require appropriate deployment with knowledge transfer, and should be considered in the context of food systems and dietary habits. Achieving nutritional goals is expected to become increasingly more challenging with climate change and increasing prevalence of carbon taxes such as the Cross-Border Adjustment Mechanism EU 'Farm to Fork' strategy (FFS) has a 20% reduction goal for fertiliser use.	[46], [49], [39], [13], [38], [44]	Climate change; Biogeochemical flows

Opportunity	System	Impact	Assumptions	Considerations	Further Reading	Planetary Boundary
Reducing freshwater consumption in urea value chain	Hydrosphere	12.8 m^3/ton of urea production [59].	Decentralised ammonia production can lead to direct use of anhydrous ammonia instead of derivatives such as ammonia.	Though anhydrous ammonia is used in large proportions in places like the USA, it is not apt for any soil and climate, and requires safety measures due to ammonia's toxicity.	[59]	Freshwater use
Increase in carbon in soil by plant growth	Biosphere	This relation is uncertain and difficult to quantify [26].	The amount of fertilisers that was absorbed by plants makes them grow, causing indirect positive effects on carbon stored in soils, forests and grasslands either through increased productivity or avoided area expansion [26] [27].	This relation is a complex one, because fertilisers also can negatively impact soil health, releasing carbon into the atmosphere [28], storage is temporary and it depends on enforcement of policies prohibiting or controlling deforestation when agriculture intensifies [26]. If deforested land is used for agriculture expansion, it leads to loss of carbon soil.	[26], [27] [28]	Climate change
Triggering acceleration of net zero transition	Atmosphere	Triggering cascade of tipping points for zero-carbon solutions in sectors covering 70% of global greenhouse gas emissions [51].	A clean ammonia tipping point in fertiliser could reduce green hydrogen prices, in turn helping unlock tipping points on clean ammonia use for shipping and steel production.	The actualization of the potential depends on many political, economic and market factors.	[51]	Climate change

Risks

Risk	System	Impact	Assumptions	Considerations	Mitigation Measures	Further Reading	Planetary Boundary
Increase in baseline Scope 3 emissions	Atmosphere	Up to 100% increase in baseline emissions from replacing urea-based fertilisers with anhydrous ammonia (AA).	N_2O emissions from anhydrous ammonia have been found to be greater than those from urea for corn and soybean in Minnesota fields, USA [54,55].	N_2O emissions depend on soil and climate local conditions. Substituting AA for urea was found to increase NO emissions [54,55].	4R: Using appropriate fertilisers based on measured emissions data for each soil and climate condition.	[44], [54, 55]	Climate change
N_2O emissions from fertiliser use	Atmosphere	N_2O emissions from synthetic fertiliser use are 0.75% of total anthropogenic GHG emissions (IPCC, 2023).	Part of nitrogen applied as fertiliser is converted to nitrous oxides and lost to the atmosphere.	N_2O emissions depend on soil and climate local conditions.	4R, microbial inhibitors, slow release fertilisers, conservation tillage, deep placement, split applications.	IPCC, 2023; [19], [18], [20], [44]	Climate change
Lost nitrogen contributing to Ocean acidification	Water	Fertiliser inputs to the seas and oceans cause 10–50% of OA near the major source regions and in marginal seas, in estuarine areas. Half of NHx emissions end up deposited to the ocean [22].	Part of nitrogen applied as fertiliser is lost and carried away to oceans as nitrates or to the atmosphere as NHx.	Amount of Nitrogen lost depends on soil, climate, management, type of application, etc.	4R, microbial inhibitors, slow release fertilisers, conservation tillage, deep placement, split applications.	[22]	Ocean acidifcation
Lost nitrogen contributing to Ozone depletion	Atmosphere	Nitrous oxides from fertiliser account of 42% of ozone-depleting potential weighted emissions [21].	Part of nitrogen applied as fertiliser is lost to the atmosphere as nitrous oxides, which react with ozone depleting it.	Amount of Nitrogen lost depends on soil, climate, management, type of application, etc.	4R, microbial inhibitors, slow release fertilisers, conservation tillage, deep placement, split applications.	[21], [56], [44]	Strato-spheric ozone depletion

Risk	System	Impact	Assumptions	Considerations	Mitigation Measures	Further Reading	Planetary Boundary
Freshwater consumption downstream	Water	Agriculture accounts for ~70% of global freshwater withdrawals, and agriculture's role in the status of this PB is estimated at the 84% level (Campbell et al., 2017).	Agriculture is an activity that consumes significant amounts of freshwater.	Climate change has a direct effect on water supply irrigation, water systems and the delivery of Water, Sanitation and Hygiene (WASH) services [44].	Reducing the use of chemical inputs; improve freshwater storage and river basin management; water management and irrigation technologies; rainfed systems; improve water governance; change water-pricing policies and subsidies.	[15]	Freshwater use
Freshwater consumption upstream	Water	Consumption for hydro, wind, solar and biomass estimated at 2.2, 5.5, 6.8 and 1100 tons/tonNH_3*.	Estimate based on cradle-to-gate planetary boundaries assessment considering global ammonia production in 2019, LCA analysis for each technology and share of safe operating assigned based on the gross value added for the whole chemical industry.		Right choice of technology (i.e. avoiding biomass-based hydrogen unless from waste); avoiding project sites in areas of water scarcity; good management practices.	[58]	Freshwater use
Aerosol loading due to fertiliser use	Atmosphere	NH_3 emissions from fertiliser use increased from 1.9 ± 0.03 to 16.7 ± 0.5 Tg N/year between 1961 and 2010.	Part of nitrogen applied as fertiliser is lost to the atmosphere as aerosols such as ammonia.		Reducing fertiliser loss or use through site specific nitrogen management, integrated nitrogen management, green manuring, conservation management, crop rotations, precision farming.	[61], [60], [44]	Atmos-pheric aerosol loading
Nitrogen input disbalancing biogeochemical flows	Biosphere, Water, Atmosphere	50 Tg of applied N fertilizer [13] lost to the environment represent 40% of the excess over the planetary boundary About 2–10% of leftover N from fertilisers enter surface and groundwater, degrades water quality [14] and results in eutrophication.	Part of nitrogen applied as fertiliser is lost to the atmosphere, hydrosphere and biosphere, disrupting the nitrogen cycles, causing eutrophication and other impacts.	The 'Farm to Fork' strategy (FFS) of the European Green Deal has a 20% reduction goal for fertiliser use.	Reducing fertiliser loss or use through site specific nitrogen management, integrated nitrogen management, green manuring, conservation management, crop rotations, precision farming; Sustainable agriculture transition; reducing demand through dietary changes and reducing food waste.	[13], [14], [24], [25], [50]	
Introduction of Novel entities in agriculture	Biosphere	105 chemical pesticides were launched or under development from 2010-2020 [62]. Concentrations of 50% of the insecticides detected exceeded regulatory thresholds [15].	Industrial agricultural practices are associated with the use and introduction to the environment of novel entities like pesticides.	The boundary states a limit of 0% introduction of untested novel entities.	Sustainable agricultural transition through minimal tillage and diversity in cultures, integrated systems of crops with livestock and trees, agroforestry, regenerative agriculture, which avoid pesticides Biological plague control; reducing demand through dietary changes and reducing food waste.	[62], [15], [33]	Novel entities

Risk	System	Impact	Assumptions	Considerations	Mitigation Measures	Further Reading	Planetary Boundary
Land system change in forested areas for deployment and agriculture	Biosphere	Croplands and pastures occupy ~40% of land surface [30]. Agriculture is the driver for around 80% of deforestation worldwide in the period 2000–2010 [15].	Agricultural production is the planet's single most extensive form of land use [15], and the biggest driver for deforestation.	Land system change for agriculture is highly dependent on policies and their enforcement. Addressing this issue should consider the broad food systems, including dietary habits (i.e. cattle ranching's role as a deforestation driver), inclusive governance and the role of indigenous peoples.	Sustainable agricultural transition through minimal tillage and diversity in cultures, integrated systems of crops with livestock and trees, agroforestry, regenerative agriculture, which avoid pesticides Biological plague control; reducing demand through dietary changes and reducing food waste.	[15], [63], [30], [44], [65]	Land system change
Agricultural practices harming biodiversity and biosphere integrity	Biosphere	NH_3 and NOx emissions have reduced forest biodiversity by more than 10% over two-thirds of Europe [64]. Agriculture expansion drives 80% of changes in biosphere integrity [15] and is the greatest driver of biodiversity loss.	Part of nitrogen applied as fertiliser is lost to the atmosphere as ammonia and nitrous oxides, which harm biodiversity. Agricultural land expansion causes loss of natural environments, harming biodiversity and biosphere integrity.	Land system change for agriculture is highly dependent on policies and their enforcement. Addressing this issue should consider the broad food systems, including dietary habits (i.e. cattle ranching's role as a deforestation driver), inclusive governance and the role of indigenous peoples.	Sustainable agricultural transition through minimal tillage and diversity in cultures, integrated systems of crops with livestock and trees, agroforestry, regenerative agriculture, which avoid pesticides Biological plague control; reducing demand through dietary changes and reducing food waste.	[15], [64], [32], [31], [44]	Biosphere integrity
Ammonia emissions or leaks harming biodiversity	Biosphere	Evidence on impacts of ammonia pollution on animals and the wider ecosystem is very limited, but are well document for plant species with decreases in both species richness and species diversity in ecosystems such as woodlands, bogs, grasslands [66].	Ammonia's toxicity, if not well managed, is a possible threat to biodiversity. Nitrogen accumulation impacts plant species diversity and composition within affected habitats [66].	Due to limited evidence, it is likely that impacts are higher than evidence suggests. Effects on animals and wide ecosystems are not well documented. It is difficult to separate effects of ammonia from nitrogen. Emissions depend on local conditions, soil and climate.	Reducing fertiliser loss or use through site specific nitrogen management, integrated nitrogen management, green manuring, conservation management, crop rotations, precision farming; substituting urea for ammonium nitrate; Security measures; deployment associated with knowledge transfer and training.	[66]	Biosphere integrity
Renewable energy production causing land use, harming wildlife and biosphere integrity	Biosphere	Impact of global production for hydro, wind, solar, biomass and current HB estimated as 0.01, 0.03, 0.1, 0.4, 0.08 %*.	Renewable energy production and deployment can present threats to wildlife safety and impact biodiversity due to material extraction, land use, leaching of toxic metals and disturbances of ecosystems [67,68].	Impacts are highly dependent on technology and site choice, local conditions, policy incentives and management.	Right choice of technology (i.e. avoiding biomass-based hydrogen unless from waste); avoiding project sites in areas of natural environments; conducting proper environmental impact assessment; good management practices.	[67]	Biosphere integrity

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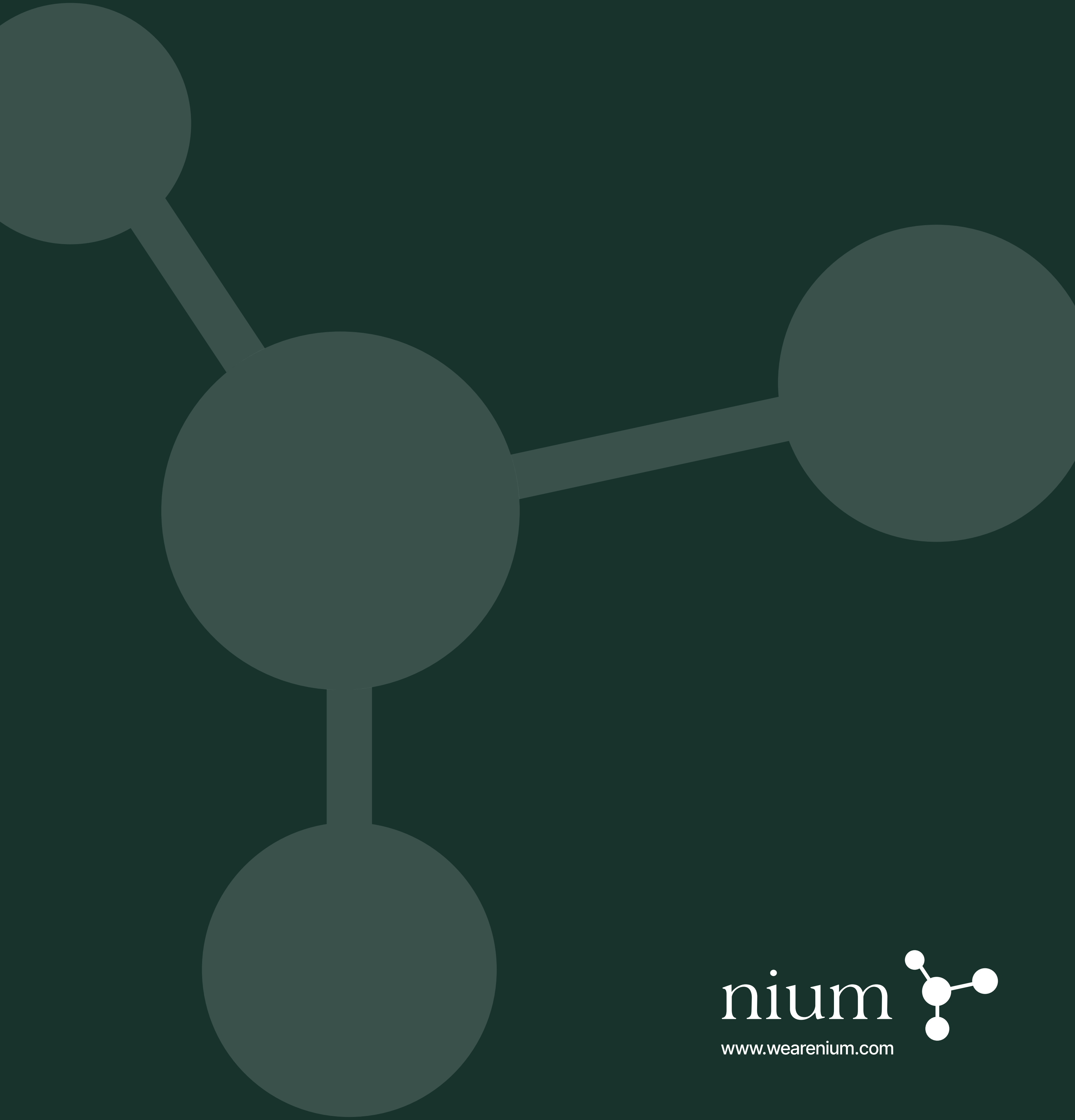

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