Threats to Nitrogen Fertilizer, Opportunities to Cultivate Sustainable Practices?

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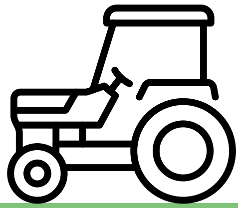

Executive Summary

WHAT IS NEW? A chain of reactions is threatening the world's food supply. Today, the price of the most widely used fertilizer (nitrogen fertilizer) is surging, with potentially devastating effects on global crop yields. It has been estimated that over 40% of the world's population depends on nitrogen fertilizer usage for food production. Facing these circumstances, the two largest exporters, China and Russia, stopped their exports to protect their food security, contributing to the growing concerns of other countries. In Switzerland, the Federal Office for National Economic Supply (FONES) released one-fifth of its emergency reserves on the market in December 2021 to avoid any supply shortages. The current war in Ukraine and sanctions against Russia are worsening the situation, highlighting the vulnerability of this market and the need to find solutions.

WHY DOES IT MATTER? The current production and use of nitrogen fertilizer are harmful to the environment, affecting air, soil, and water quality. Thus, this document explores the opportunity that arises from this challenge, namely to build-back-better: how to preserve food security while reducing the adverse effect of food production on the environment?

WHAT COULD BE DONE? Shifting towards more sustainable practices while maintaining a viable level of food supply can be attained through several channels. Increasing nitrogen use efficiency (reducing loss and improving uptake), reducing food waste, and adapting our diets are the most promising and synergistic approaches. A large-scale study showed that improvement in nitrogen use efficiency (NUE) led to an average yield increase of 11.2%, a 15.6% decrease in nitrogen fertilizer, and a decrease of 7.7% in CO_2 emissions. Achieving this agricultural transition will require a paradigm change, ambitious policies, and extensive public investments.

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1. OVERVIEW OF THE SITUATION

A chain of reactions is threatening the world's food supply. While over 40% of the globe's population depends on nitrogen fertilizer usage for food production (Erisman et al., 2008), fertilizers price are surging, impeding global crop yields. This challenging situation is an opportunity to rethink our food production processes and methods. Nitrogen fertilizers are often over-used and can have severe adverse effects on the environment. This report aims at putting forward the current mechanisms at play as well as exploring potential solutions to maintain food security while reducing the destructive effect of the current approaches.

1.1. Threats to production

The price of urea - the most commonly used nitrogen fertilizer - has more than doubled over the last four months of 2021 (see **Figure 1**). This surge in price and decrease in production is partly associated with rising natural gas prices and the energy transition. More precisely, nitrogen fertilizer synthesis requires *hydrogen* and natural gas in its most common production process (fossil fuel steam reforming). As the EU is set to transition to zero emissions by 2050, gas demand will likely continue to rise at least until the 2040s, putting further pressure on a core component of nitrogen fertilizer (Stern, 2020).[1] The multiplication of export barriers in countries producing nitrogen fertilizer, as well as logistical problems mixed with global bad weather highlight and potentially aggravate the situation. China and Russia (the top two exporters of urea, see **Figure 2**) respectively stopped[2] and imposed a quota[3] on their exports

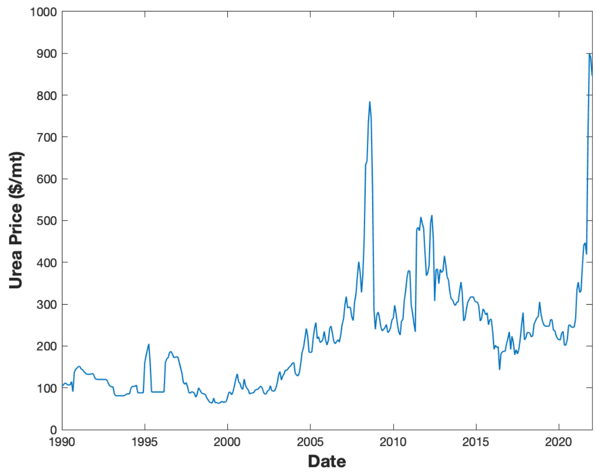

Figure 1: Evolution of urea monthly nominal price
(Source: World Bank)

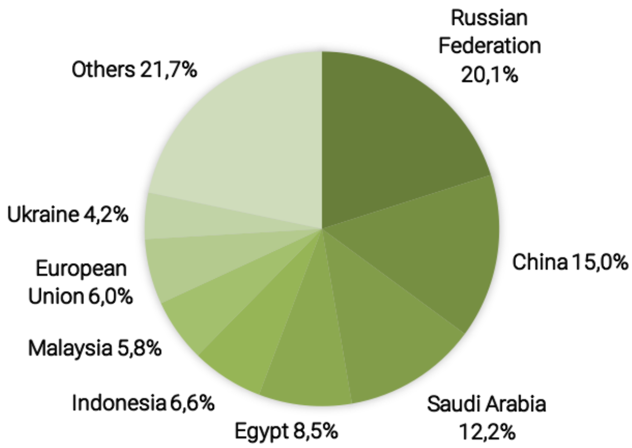

Figure 2: Share of urea exports in 2020
(Source: WITS - World Bank)

1 Note that the relationship between agriculture and gas prices is complex. In the United States for example, recent biofuel encouragement policies made natural gas prices more dependent on crop prices, which complicates the direction of the association between the two commodities (Bekkerman et al., 2021).

2 China's major fertilizer makers to suspend exports amid tight supplies on summer 2021 (Reuters).

3 Russia will set 6-month quotas for exports of nitrogen fertilizers on winter 2021 (Reuters).

of nitrogen fertilizer. In December 2021, the Swiss Federal Office for National Economic Supply (FONES) has decided to release 20% of the mandatory nitrogen reserves held (Département fédéral de l'économie, de la formation et de la recherche, 2021).

The recent conflict between Ukraine and Russia and the political reactions resulted in the suspension of the Nordstream 2 pipeline license. These events exacerbate uncertainties on an already tense situation and could lead to an additional increase in the price of natural gas and shortage of fertilizers.

1.2. Why are nitrogen fertilizers important?

Nitrogen is a critical compound needed by most plants for their growth, necessary for creating proteins and DNA. Historically, agricultural production did not use synthetic fertilizers to provide nutrients to the crops. Instead, it relied on recycling animal manure and human waste, on *crop rotation* to restore soil fertility, and on *nitrogen fixation* by legumes. Please refer to **Box 1** for a description of the different types of existing fertilizers and to **Box 2** for further details on the nitrogen cycle.

Food production accelerated in 1909 with the discovery of the Haber-Bosch process that kick-started the *green revolution* by allowing the production of synthetic fertilizers on an industrial scale. Since then, the use of nitrogen fertilizers has dramatically increased – more than 20-fold between 1950 and 2000 (Bouwman et al., 2013). This trend is driven by the need to support a growing population, the increase in meat consumption and associated animal feed, and the intensification of agriculture.

Box 1 - Different Types of Fertilizers

Organic vs. Inorganic Fertilizers: the first major difference is the components the fertilizer is based on. A fertilizer can be categorized as organic if it is made with bio-degradable components (manure, compost, worm, etc.) or as inorganic if it is based on synthetic chemical compounds (urea, anhydrous ammonia, etc.) that are not bio-degradable (Hazra, 2016). Massri and Labban, 2014 compared the yield of watermelons (Citrillus lanatus) grown with organic and non-organic fertilizers. The results indicate that yields are higher using chemical fertilizers, but watermelons' quality (size, aspect, and color) is superior for those grown using organic fertilizers.

Chemical Nutrient-Based Fertilizers (NPK): when discussing chemical fertilizers, it is common to distinguish them according to the different nutrients they contain. The three primary *macro-nutrients* are nitrogen (N), phosphorus (P), and potassium (K). Nitrogen is essential for the plant's growth, its size enlargement and yield production. Phosphorus is also important for the continuous plant growth and root fortification. Finally, potassium is vital for stalk reinforcement while also playing an important role in protecting the plant from pests and diseases (Roy and Finck, 2006). Secondary *macro-nutrients* are calcium (Ca), magnesium (Mg), and sulfur (S).

Without fertilizers, today's food supply would not cover the rising demand. The growing world population, especially in regions already experiencing nitrogen scarcity, is expected to make the situation only more salient in the future (Liu et al., 2016).

1.3. Environmental impacts

Although the large-scale usage of nitrogen fertilizer has allowed an increase in yields and food production, it is impossible to ignore its associated environmental consequences. In addition to greenhouse gases (GHG) emitted

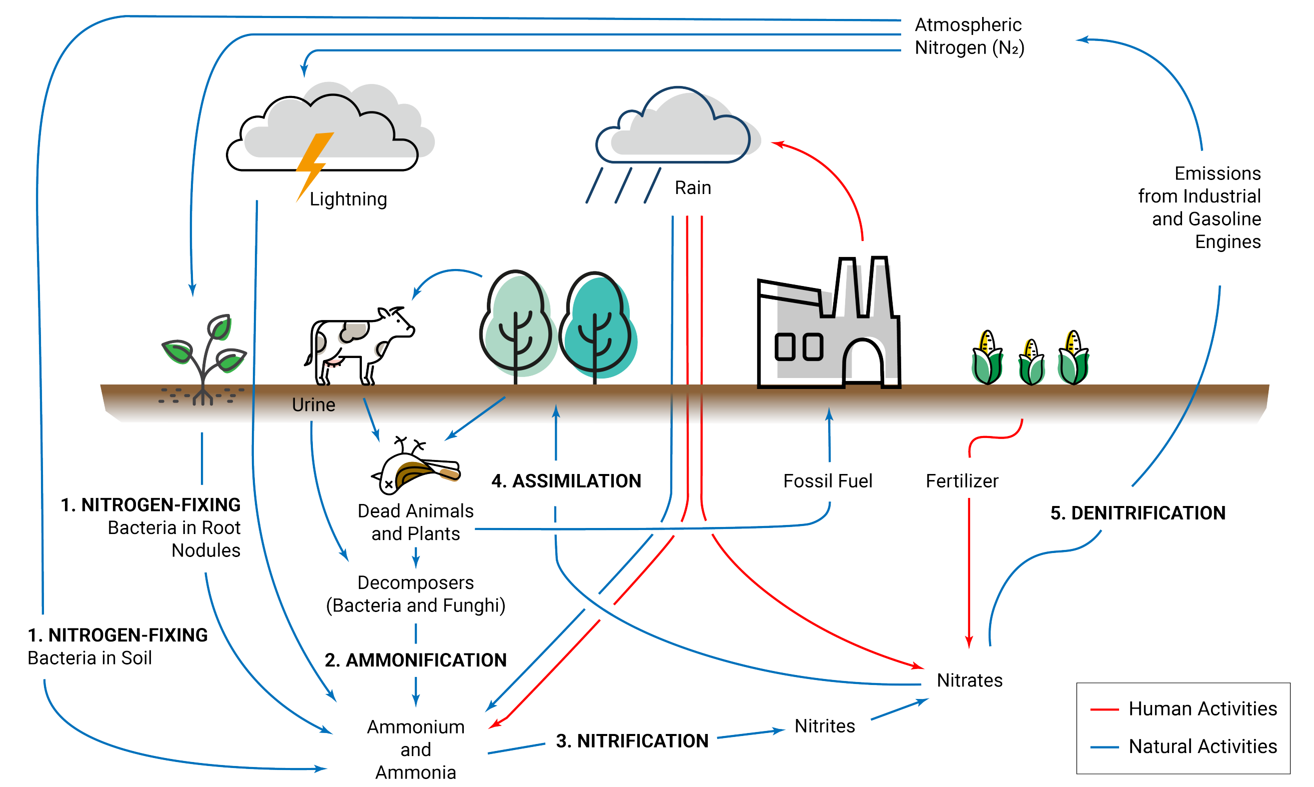

Figure 3: Nitrogen Cycle (adapted from Encyclopedia Britannica)

Box 2 - The Nitrogen Cycle

The nitrogen cycle can be summarized as a sequence of different steps (retrieved from **Fondriest**):

1. **Nitrogen Fixation**: under the impulse of specific bacteria and cyanobacteria present in the soil, *nitrogen fixation* corresponds to the process during which nitrogen in gaseous form (N_2) is transformed into ammonia (NH_3).

2. **Ammonification**: during this process, various microorganisms convert organic nitrogen from dead animals and plants into ammonia and ammonium (NH_4^+).

3. **Nitrification**: during this step, ammonia (or ammonium) is converted into nitrate (NO_3^-). This transformation takes place in two steps: first, ammonia is transformed into nitrite (NO_2^-) and then oxidized into nitrate.

4. **Assimilation**: this stage occurs when the plants assimilate the nitrate produced during the previous stage through roots. It then passes into animals through the ingestion of the plants.

5. **Denitrification**: it is the last step in the nitrogen cycle. It occurs when specific types of bacteria take up nitrate and convert it into nitrogen gas, which is released into the air.

Figure 3 illustrates this process while separating the human and natural processes.

during the fertilizer production process, the use of nitrogen fertilizers emits nitrous oxide (N_2O), a gas whose global warming potential is significantly larger than CO_2 (IPCC, 2013). In China for instance, fertilizer-induced emissions account for nearly 50% of greenhouse gas emissions arising from crop production (Wang et al., 2017). The use of nitrogen fertilizers also induces a risk of overuse which directly threatens biodiversity and ecosystems, soil (through acidification), water (e.g., *eutrophication*, see **Box 3**), air quality, and consequently human health (Sutton et al., 2011; Cassman et al., 2003; Arnold, 2006; Tian and Niu, 2015).

On a global scale, large discrepancies exist among farmers' awareness of fertilizer and pesticide use and their impact on the environment. Higher awareness leads to more sustainable farming (Lithourgidis et al., 2016). By contrast, farmers that have little experience with fertilizer application tend to couple over-application of nitrogen fertilizer with nutrient-lacking soil, which deteriorates soil fertility even further (Abay et al., 2021; Sanchez, 2002). Therefore, education specifically related to nitrogen fertilizer use and good practices can be beneficial at a large scale.

The elements mentioned above illustrate the need to find alternative ways to reduce the fossil-fuel reliant production and consumption of nitrogen fertilizers. For this purpose, three options are explored in this paper:

1. Improving nitrogen use efficiency (NUE) (**Section 2**)
2. Reducing the demand through combating food waste and encouraging behavioral changes among consumers (**Section 3**).
3. Bypassing the need for natural gas by producing *hydrogen* differently through water electrolysis (**Section 4**).

These options, while promising, are not immediate solutions to the sudden surge in nitrogen fertilizer price. To build-back better requires a change of paradigm, discussed in **Section 5**.

Box 3 - Example: Consequence of Nitrogen Fertilizer on Ground Water Contamination

Not all fertilizer applied to crops ends up on our plate. Some of it can be found in water grounds or surfaces. Nitrogen water pollution is destructive: making water unsafe to drink, affecting biodiversity, causing *eutrophication* which damages fisheries or, more generally, marine environments (Bijay-Singh and Craswell, 2021).

As such "crop production represents the largest single factor perturbing the nitrogen cycle" (ibid., p.2). The nitrates present in the soil after nitrogen fixation can dissolve in water through rain or irrigation and then leach through the soil into underground water bodies. Excessive nitrogen fertilizer applications exponentially increase *nitrate leaching* (Goulding et al., 2000; Wang et al., 2017).

The most effective way to tackle the problem is by using best practices in its appliance (e.g., not exceeding recommended appliances) coupled with water management which can reduce *nitrate leaching* into the underground water by around 58%. Other effective strategies are fertilizer management (applying the optimal amount), and structural adjustments such as applying *biochar* (which increases soil nitrogen retention) or using a *crop rotation* system (Bijay-Singh and Craswell, 2021).

As climate change affects weather patterns severely, such as increasing heavy rainfall, the already notoriously tricky issue of potential water contamination by nitrogen fertilizer application is becoming even more tedious. Sustainable agriculture will require further improvement in fertilizer efficiency (see **Section 2**).

2. NITROGEN USE EFFICIENCY: SOIL MANAGEMENT & NITROGEN LOSS

Is it possible to reduce nitrogen fertilizer usage while increasing crop yields? Surprisingly, the answer to this question can be positive. The seemingly simple concept behind this promising approach is to improve nitrogen use efficiency (henceforth, NUE). In fact, with current usage, approximately half of the nitrogen applied on crops is lost in nature (Luis Lassaletta et al., 2014).

2.1. International discrepancies in NUE

There are substantial disparities in the world with respect to nitrogen use and its efficiency. For example, Bolivia uses 100 times less fertilizer per *arable land* than New Zealand (WDI FAO data 2018). In short, the consumption of fertilizer is highly correlated with GDP (Liu et al., 2016). However, those differences are also related to the type of crops used, the local climate, and the soil nature and quality.

NUE can be defined as the percentage of nitrogen available retained by the crop. In 2014, some countries such as France had an NUE of 73%, while neighboring Spain had an NUE of only 36% and Portugal 19% (Switzerland: 37%). A two- or three-fold difference in NUE between some countries, in addition to the relatively low world average since the 80s (around 47%), are a sign that there is room for improvement (Luis Lassaletta et al., 2014).[4] A study in China revealed that optimizing the use of various agricultural inputs can nearly double the yield without increasing the total nitrogen use (X.-P. Chen et al., 2011) (see **Section 2.3.**). That approach would allow killing two birds with one stone: maintain crop yield while reducing adverse environmental effects.

2.2. Practices to improve NUE

Implementing appropriate management strategies can improve NUE by maximizing the plants' nitrogen uptake and minimizing environmental losses. However, optimal nitrogen fertilizer use results from complex interactions between the crops, soil, and climate. With the progress of sciences such as *agroecology*, our knowledge of these interactions deepens, and models using weather and soil data are developed to optimize NUE. These methods could increase yields and farmers' income while reducing nitrogen use and greenhouse gases emissions (Cui et al., 2018). In the following, we briefly discuss several practices that can improve NUE.

Fertilization process

Several nitrogen fertilizers exist on the market, each of them with specific properties that influence their effectiveness as a nitrogen carrier. For instance, the most common nitrogen fertilizer, urea ($CO(NH_2)_2$), contains 46% nitrogen, while anhydrous ammonia

4 Note that a very high value of NUE (above 90% is undesirable as it might imply that the stock in the ground is depleting (Hutchings et al., 2020)).

(NH_3) contains 82% nitrogen. Soil and crops will respond differently depending on the type of fertilizer used. Applying the adequate quantity is thus challenging, and, as a result, farmers in developed countries often over-fertilize, as a form of insurance (Fageria and Baligar, 2005). The methods of application also affect the nitrogen uptake efficiency. For example, studies show that applying fertilizers once during crop growth intensifies nitrogen loss via *leaching* and denitrification. Instead, farmers should favor splitting nitrogen fertilizer application (ibid.).

Soil conditions

The uptake of nitrogen by plants strongly depends on the soil conditions such as soil acidity and moisture. Soil acidity adversely affects plant growth by reducing the uptake of nutrients (Marschner, 1991). Liming reduces acidity and increases yields (Fageria and Baligar, 2005). Similarly, adequate soil moisture is critical during crop growth. Water deficit slows down nitrogen movement, while excessive irrigation leads to nitrogen loss due to *leaching* and denitrification (Benjamin et al., 1997; Drury et al., 2003; Lehrsch et al., 2001).

Animal manure

The use of animal manure can increase the soil content in nitrogen and improve the soil's physical and biological properties (Clark et al., 1998; Irshad et al., 2002). Interestingly, complementary applications of synthetic fertilizers and animal manure can increase nutrient use efficiency and soil fertility (Makinde and Agboola, 2002; Yaduvanshi, 2003). However, over-application of manure can also lead to groundwater pollution (Sharpley and Smith, 1995).

Crop rotation

A traditional agriculture practice used for centuries, *crop rotation* increase nutrient and water use efficiency, improve soil quality, and can even help limit disease and weeds (Francis and Clegg, 2020; Karlen et al., 1994). Alternating legumes and crops reduce the nitrogen requirements of cereals thanks to the biological *nitrogen fixation* by legumes (Jensen, Carlsson, et al., 2020). Specifically, legumes develop a symbiotic relationship with the soil bacteria Rhizobia, which fixes atmospheric nitrogen (see **Box 1**), thus reducing the need for synthetic fertilizers. Legume-based pastures can consume 35% to 60% fewer chemicals than cereals produced through nitrogen fertilizer-based crops (Jensen, Peoples, et al., 2012).

Crop residue and green manure

NUE can also be improved thanks to good management of crop residues, i.e. portions of plants remaining after seed harvest. Incorporating these residues into soil provides substantial nutrients for succeeding crops (Ambus and Jensen, 2001). Similarly, green manuring - the process of growing plants with the purpose of incorporating them underground - can supply additional nutrients to the soil. In particular, legumes are interesting green manure due to their biological *nitrogen fixation*. However, the benefits depend on the soil conditions, the legumes' ability to fix nitrogen, and their growth requirements to be economical to produce (Fageria and Baligar, 2005).

Biostimulants

Biostimulants can increase NUE, *abiotic stress* tolerance, and soil and crop quality. There are two subcategories of biostimulants, namely biofertilizers and biocontrols. The former is defined by its ability to increase nutrient use efficiency, whereas the latter is used to battle pathogens (du Jardin, 2015). For example, microorganisms such as *Azotobacter* and *Rhizobium* are biofertilizers that develop symbiotic relationships with the roots of plants and boost the *nitrogen fixation* process.

The biostimulant market has been steadily growing, and is often hailed as a solution to construct a sustainable agriculture. Indeed, some studies demonstrate that biofertilizers could be cost-effective, increasing plant growth by 10%-40% (Nosheen et al., 2021), and an environmentally friendly alternative to chemical fertilizers (Amoo et al., 2021). By contrast, others cannot find a link between applying specific biostimulants and an increase in yield or productivity (Carvalho et al., 2014; Rodrigues et al., 2018).

The assessment of the effect of biostimulants on crops is complex, mainly due to interaction with conventional fertilizers, pesticides, and heterogeneity among soil properties (Nosheen et al., 2021; Schütz et al., 2018). Still, drylands seem particularly well suited for the use of biostimulants due to their specific microbial community. With increasing temperatures across the globe, biostimulants may become a crucial tool of future agro- strategy (Schütz et al., 2018). The biostimulant market thus holds significant promise for new discoveries, which could help replace part of traditional agricultural additives (Yakhin et al., 2017).

2.3. Case study: China

More than 21 million farmers, representing a cumulative 40 million hectares, have been involved in an experiment to increase the NUE for maize, rice, and wheat, from 2005 to 2015 (Cui et al., 2018). The crop yields increased by 11.2% on average. The nitrogen fertilizer use decreased by 15.6%, while the NUE increased by more than 30%.[5] Finally, the CO_2 emissions were cut by 7.7%.

In this experiment, the researchers used an integrated soil–crop system management (henceforth ISSM). ISSM uses weather and soil data to determine the most efficient crop to plant for a given place, its optimal quantity and when to apply fertilizer, and water.

The study went significantly beyond simply giving written road-maps. Five types of measures were implemented: workshops, on-site guidance, high-quality production materials were provided (e.g., fertilizers, seeds), field-day meetings, and the ISSM recommendations were printed and freely shared with a calendar.

Undoubtedly, improving NUE with ISSM or even more advanced methods such as precision agriculture[6] should be considered worldwide. But can we expect similar outcomes in the rest of the world? The variety of soil and ecosystems in China helps extend the conclusion of this research to other regions of the world. China has a very long coast, as well as some of the

5 The definition of NUE used in the paper is kg of nitrogen per kg of grain.

6 Precision agriculture is a management strategy relying on the use of precise information on soil, weather, crop conditions, at a high spatial resolution and dynamically. Additionally, it could be combined with advanced tools allowing to provide what the plant needs at a granular

highest peaks in the world, it also has most of what is in between: deserts, tundra, steppes, forests etc. It is important to note that NUE was relatively low at the beginning of the study (27%, Luis Lassaletta et al., 2014), leaving more room for improvement than in countries with already higher NUE levels.

Additionally, the study focused on smallholder farming, making it even more relevant internationally. Smallholder farming is the dominant form of farming in China, India, Sub-Saharan Africa, representing half of the world population (Fritz et al., 2015).

level.

3. FOOD WASTE, BEHAVIOR AND DIET

3.1. Reducing food waste

From crop to plate, around one-third of the global food production is lost or wasted (C. Chen et al., 2020; Liu et al., 2016). Within the European Union, 60 million tons of food are wasted annually, accounting for an equivalent of 16% of the food consumed in all member states (Vanham et al., 2015). In turn, avoidable food waste makes up 47 million tons, representing 12% of the food reaching consumers annually (ibid.). Reducing food waste is the United Nation's Sustainable Development Goal number 12. It represents tackling inefficiency within the global food systems, because when food is wasted, demand for food production increases. Food waste also has environmental impacts, such as releasing greenhouse gases (C. Chen et al., 2020). Of the total environmental damage in the EU, 15-16% are associated with food waste (ibid.).

Not surprisingly, food waste also involves a significant nitrogen footprint. It is estimated that the amount of nitrogen contained in avoidable food waste represents 0.68 kg per person per year on average in the EU (Vanham et al., 2015). Within the category of avoidable food waste, one can further distinguish between nitrogen that stems from the production process of food and nitrogen that is contained in consumed food. The food category with the highest amount of avoidable nitrogen wasted during the production process is meat. This situation can be explained by the fact that meat production requires many resources (see **Section 3.2.**). Conversely, in the category of avoidable waste of consumed nitrogen, cereals account for the largest nitrogen losses (ibid.). This is due to the disposal of unused resources.

> ***It is estimated that the amount of nitrogen contained in avoidable food waste represents 0.68 kg per person per year on average in the EU.***

The average amount of nitrogen required to produce European avoidable food waste is equivalent to the annual use of inorganic fertilizer for England and Germany combined (Vanham et al., 2015). Besides the need to reduce meat consumption, a large share of the vegetable production is also wasted in China, East Asia, and Pacific. This means that policies targeting crop consumption (e.g., education or intervention campaigns) could be highly effective in those countries (C. Chen et al., 2020).

3.2. Behavior and dietary change

In addition to food waste management, changes in consumers' diets can significantly impact the demand for nitrogen fertilizers. The main viable behavioral change lies in switching to less meat-intensive and more legumes-based diets.

Vegetarian diets or diets including less meat mechanically require less fertilizer use because of the difference in fertilizer needed to produce a plant-based calorie compared to a meat-based one. More specifically, producing 1000 animal kilo-calories (kcal) requires on average 84 g of nitrogen fertilizer compared to only 16 g of nitrogen fertilizer for producing 1000 kcal of plant-based calories (Liu et al., 2016). Depending on the type of meat consumed and the way livestock is fed, these numbers can greatly vary, but the ratio of one of meat-based food needs to the vegetal food fertilizer needs is considerable.

As suggested by Westhoek et al., 2015, "the current average nitrogen footprint per person differs by a factor 2-4 between European countries, mainly due to differences in average food consumption patterns". Reducing livestock production and consumption can therefore help reduce the general environmental footprint of nitrogen fertilizers on the environment by reducing the need for animal-feeding crops (Henk Westhoek et al., 2014). However, a shift to a plant-based diet would also reduce the livestock population that is currently the first source of manure, a major complement and alternative to nitrogen fertilizer.

Furthermore, as discussed in **Section 2**, the efficiency of nitrogen fertilizers depends greatly on the way the soil is managed and the degree of diversification of the crops (Nemecek et al., 2015). In particular, one of the most promising complements to drastically reduce nitrogen fertilizer use while keeping high agricultural yields consists in introducing legumes that can supply nitrogen (N) to agro-ecosystems and thus reduce the requirements for synthetic fertilizers (see **Section 2.2.** for more details). These insights suggest that, beyond their well-documented health benefits in terms of high-protein and low-fat content (Polak et al., 2015), a higher consumption of legumes could increase the demand for them and render their use for higher yields more attractive for farmers.

4. AN ALTERNATIVE PROCESS FOR HYDROGEN PRODUCTION: WATER ELECTROLYSIS

The main costly component of nitrogen fertilizer production is the production of hydrogen, a necessary input for the synthesis of nitrogen fertilizer. Current state-of-the-art technologies offer more than twenty different methods for producing *hydrogen*, at different development stages (Acar and Dincer, 2019; Baykara, 2018; Dincer and Acar, 2015). Today, the cheapest and most used technology (around 80% of today's production) is fossil fuel reforming which consists in separating (di)-hydrogen molecules from hydrocarbons such as methane (CH4) with an average of 0.75$ per kg of *hydrogen* produced (Dincer and Acar, 2015). The main setback of this technology for *hydrogen* production is that CO_2 is a necessary output of the process, leading observers to label it grey *hydrogen* production. Capturing some of the emitted CO_2 alleviates this technology's environmental damages – label blue *hydrogen* production – at the expense of significantly increasing production costs.

Out of the many other technologies to produce *hydrogen*, one of the most mature is water electrolysis, which consists of separating *hydrogen* from oxygen in water by applying an electric current. The fact that this technology has no direct carbon emissions leads experts to label it as green *hydrogen*. With current electricity prices, this technology produces *hydrogen* that is three to four times more expensive than fossil fuel reforming depending on the specific electrolysis technique and electricity prices (Bartels et al., 2010; Dincer and Acar, 2015). This high cost makes it much less economically attractive than fossil fuel reforming, especially with low carbon prices (Lemus and Martínez Duart, 2010). However, several elements can favor of green *hydrogen* to become more economically competitive than grey *hydrogen*:

- First, an increase in methane price due to a sustained demand[7] and uncertainties on supply can render fossil fuel reforming more expensive.
- Second, with more stringent environmental policies, the increase of carbon prices[8] can significantly increase the cost of production of grey *hydrogen*, making blue and green *hydrogen* more economically competitive.
- Third, public investments in research and development for projects in green *hydrogen* can lower the production cost of non-CO_2-emitting technologies by paying for a share of initial investment cost in electrolyzers and stimulating cost improvements through learning curve benefits.[9]

7 For power production, heating, transport and even for fertilizer synthesis.

8 Note that CO_2 price has tripled in 2021 after stagnating below 30e a ton since its creation in 2005.

9 France and Germany recently announced investments of around 10e billion in hydrogen related projects for instance.

5. INSIGHTS ON THE WAY FORWARD

The threats to the production of synthetic fertilizers and the environmental impacts associated with their use represent an opportunity to build back better. Although we discussed several promising solutions in this document, each independent action is not enough. Instead, a change of paradigm would be necessary for obtaining notable results.

> ***A mix of instruments needs to be implemented to better inform consumers about their impacts, to align prices with the "true cost of food", and to provide farmers with appropriate training and financial support.***

A systemic change could be enhanced by self-reinforcing synergies. Lowering per capita food demand in high-income countries could also facilitate the transition towards sustainable farming and a more circular vision that aims to transform nitrogen losses into inputs. For instance, Billen et al., 2021 show that it is feasible to feed Europe in 2050 while drastically reducing nitrogen losses by combining dietary change towards fewer animal products, *crop rotation*, and optimal reuse of manure connecting livestock and crop cultivation.

However, shifting agricultural practices towards less environmentally harmful production processes face a significant challenge. Almost a century of crops increasingly relying on nitrogen fertilizers led to massive gains in terms of innovation and learning (Arthur, 1989). This strong path dependency increases the technological lock-in in synthetic fertilizer usage we are experiencing today (Marra et al., 2003). Therefore, the move towards greener and potentially more efficient technologies will probably entail accepting a period of high-investment with reduced returns to change the paradigm successfully (Cowan and Gunby, 1996). In other words, for cleaner technologies to become market competitive and for current actors of the market (farmers, multinationals, governments) to switch their practices, heavy investments in new processes and infrastructure will be necessary.

Achieving this agricultural, technological and behavioral transition calls for ambitious policies. Currently, the environmental and social impacts along the food supply chain are not (fully) taken into account when producing and consuming food. Thus, accurately measuring these externalities is the first step to fostering sustainable behaviors and *agroecology* practices. Then, a mix of instruments needs to be implemented to better inform consumers about their impacts (e.g., via labels), to align prices with the "true cost of food" (e.g., via financial incentives), and to provide farmers with appropriate training and financial support. Arduous challenges to overcome but with objectives worthwhile attaining.

GLOSSARY

Abiotic stress: "Nonliving environmental factors (such as drought, extreme cold or heat, high winds) that can have harmful effects on plants" (Biology Online).

Agroecology: "the study of the interactions between plants, animals, humans and the environment within agricultural systems" (Dalgaard et al., 2003)

Arable land: "land under temporary crops (double-cropped areas are counted once), temporary meadows for mowing or for pasture, land under market or kitchen gardens, and land temporarily fallow" (FAO).

Azotobacter: "any of a genus (Azotobacter) of large rod-shaped or spherical bacteria occurring in soil and sewage and fixing atmospheric nitrogen" (Merriam- Webster). See also Nitrogen fixation and Rhizobium.

Biochar: "[...] the carbon-rich product when biomass, such as wood, manure or leaves, is heated in a closed container with little or no available air. [...] [I]t distinguishes itself from charcoal and similar materials [...] by the fact that biochar is produced with the intent to be applied to soil as a means of improving soil productivity, carbon (C) storage or filtration of percolating soil water" (Lehmann and Joseph, 2009, p. 1).

Crop rotation: "the successive cultivation of different crops in a specified order on the same fields, in contrast to a one-crop system or to haphazard crop successions" (Encyclopedia Britannica).

Eutrophication: "the enrichment of freshwater bodies by inorganic plant nutrients (e.g., nitrate, phosphate), occurring either naturally or as a result of human activity (e.g., fertilizer leaking into groundwater)" (Lawrence, 2008)

Green revolution: "great increase in production of food grains (especially wheat and rice) that resulted in large part from the introduction into developing countries of new, high-yielding varieties, beginning in the mid-20th century" (Encyclopedia Britannica).

Hydrogen (green, blue and grey):

- *Green hydrogen*: "[...] also referred to as "clean hydrogen" is produced by using clean energy from surplus renewable energy sources, such as solar or wind power, to split water into two hydrogen atoms and one oxygen atom through a process called electrolysis" (World Economic Forum).

- *Grey hydrogen*: "[...][it is] the most common form and is generated from natural gas, or methane, through a process called "steam reforming"" (World Economic Forum).

- *Blue hydrogen*: "[...] whenever the carbon generated from steam reforming is captured and stored underground through industrial carbon capture and storage (CSS)" (World Economic Forum).

Inoculum: "process or technique that involves transferring microorganisms from culture for growth. Thus, in microbiology, the term inoculum refers to the material in which microbiologists used for inoculation, i.e., the introduction of microorganisms into a culture medium" (Biology Online).

Macro-nutrient: "chemical element or substance (such as potassium or protein) that is essential in relatively large amounts to the growth and health of a living organism" (Merriam-Webster).

Nitrate leaching: "leaching is the process by which chemicals (e.g., nitrates) in the upper layer of the soil dissolves (e.g., because of too much irrigation) and moves to the lower layers" (Lawrence, 2008)

Nitrogen fixation: "[...] any natural or industrial process that causes free nitrogen (N_2), which is a relatively inert gas plentiful in air, to combine chemically with other elements to form more-reactive nitrogen compounds such as ammonia, nitrates, or nitrites" (Encyclopedia Britannica).

Rhizobium: "soil bacteria capable of forming symbiotic nodules on the roots of leguminous plants and of there becoming bacteroids that fix atmospheric nitrogen" (Merriam-Webster). See also Nitrogen fixation.

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