Environmental and Health Impacts of Pesticides and Fertilizers and Ways of Minimizing Them

Envisioning A Chemical-Safe World

Chapter 10 of 12

The impact of fertilizer use

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About

In December 2017, Resolution 4 of the 3rd Session of the United Nations Environment Assembly (UNEA 3) requested "the Executive Director to present a report on the environmental and health impacts of pesticides and fertilizers and ways of minimizing them, given the lack of data in that regard, in collaboration with the World Health Organization (WHO), the Food and Agriculture Organization of the United Nations (FAO) and other relevant organizations by the fifth session of the United Nations Environment Assembly". In response to this request, UNEP published a *Synthesis Report on the Environmental and Health Impacts of Pesticides and Fertilizers and Ways to Minimize Them*[1] in February 2022 (United Nations Environment Programme [UNEP] 2022).

The overall goal of the synthesis report is to provide the information base to enable other advocacy actions to be taken by stakeholders to minimize the adverse impacts of pesticides and fertilizers. Specific objectives of the synthesis report are to:

- Update understanding of current pesticide and fertilizer use practices;
- Present major environmental and health effects of pesticides and fertilizers, during their life cycle, and identify key knowledge gaps;
- Review current management practices, legislation and policies aimed at reducing risks in the context of the global chemicals, environmental and health agenda;
- Identify opportunities to minimize environmental and health impacts, including proven and innovative approaches.

This chapter on "The impact of fertilizer use" is the 10th in a series of 12 chapters that make up a comprehensive compilation of scientific information. The chapters were developed to both inform and further elaborate on the information provided in the synthesis report. Please note that the disclaimers and copyright from the synthesis report apply.

1 The Synthesis report is available at https://www.unep.org/resources/report/environmental-and-health-impacts-pesticides-and-fertilizers-and-ways-minimizing.

The impact of fertilizer use

10.1 Overview

> With fertilizers, we face a kind of Goldilocks problem. Some places have too few nutrients and therefore poor crop production, whereas others have too much, leading to pollution. (Foley 2011, pp. 64-65)

Much is still unknown about the adverse environmental and health effects of fertilizers. As emphasized in Chapter 9, the links between fertilizer use and human health, for example, are not fully understood and quantifying the effects of fertilizer use is complex. Large information gaps exist with regard to the impact of fertilizers. In the case of some of the information currently available, there are concerns about reliability and the comparability of data from different studies.

More is known about fertilizers' agronomic and economic benefits. But even in the case of agronomic and economic effects, fertilizer is usually part of a technology package. Where data exist, it is difficult to compare those from different studies since assumptions may vary among the studies. [Chapters 10.2, 10.3 and 10.4]

Fertilizers are used for their "provisional" role. Their main benefits include provision of food, feed and fibre. Fertilizers support food security and can contribute to the provision of nutritious food and feeds (in terms of both quality and quantity) through agronomic biofortification (Global Panel on Agriculture and Food Systems for Nutrition 2016a; Joy *et al*. (2017). (Chapters 10.1, 10.3.1 and 10.3.3]

Few attempts have been made to quantify the adverse effects of fertilizer use, including through their overuse and contaminants. Doing so can be complex. Studies have suggested that the monetary costs could be substantial (van Grinsven *et al*. 2013; Sobota *et al*. 2015; Zhang *et al*. 2020). [Chapters 10.2.1 and 10.2.3]

Direct health impacts of fertilizers are rare, but may occur through, for example, inhalation of ammonia and dusts from manure. Storage and transport accidents involving fertilizers may cause significant loss of human life (Zhao 2016; Guglielmi 2020). [Chapter 10.2.1]

The planetary boundary for nitrogen and phosphorus flows is considered to have been crossed (Stockholm Resilience Centre 2020). Agricultural production has been identified as a major driver for the exceedance of planetary boundaries, with overfertilization and low nutrient use efficiencies contributing to nutrient losses (Campbell *et al* 2017). [Chapter 10.2.2]

The use of fertilizers provides economic benefits for various stakeholders. Their use by farmers is mostly profitable and can contribute to better livelihoods for farming households (Donkor *et al*. 2019; Martey, Kuwornu and Adjebeng-Danquah 2019). Nevertheless, farmers sometimes incur fertilizer-related losses (Kelly 2005). [Chapter 10.3.2]

Excessive use increases fertilizers' negative effects on ecosystem services. On the other hand, their sustainable use can reduce these effects and even generate ecosystem benefits, for example through increasing soil carbon or avoiding conversion of forests and pastures to cropland, which in turn reduces loss of ecosystem services (Han *et al*. 2016; Tang *et al*. 2019). [Chapters 10.2.2 and 10.3.4].

10.2 Environmental and health costs

Despite indications that fertilizers can have negative effects on the environment and health, there are no global studies on the total costs of fertilizer pollution. However, studies have attempted to estimate the global or regional impacts of some pollutants that could potentially be from fertilizer.

Following the literature review conducted under this report, scientific research appears to be more focused on nitrogen than on other potential pollutants from fertilizers. Scientists have attempted to bring the world's attention to the nitrogen issue through numerous publications and the creation of an international platform (International Nitrogen Management System 2021). In 2019 scientists sent an open letter to the Secretary-General of the United Nations requesting that global action on nitrogen be mobilized (UK Centre for Ecology and Hydrology 2019).

10.2.1 Human health

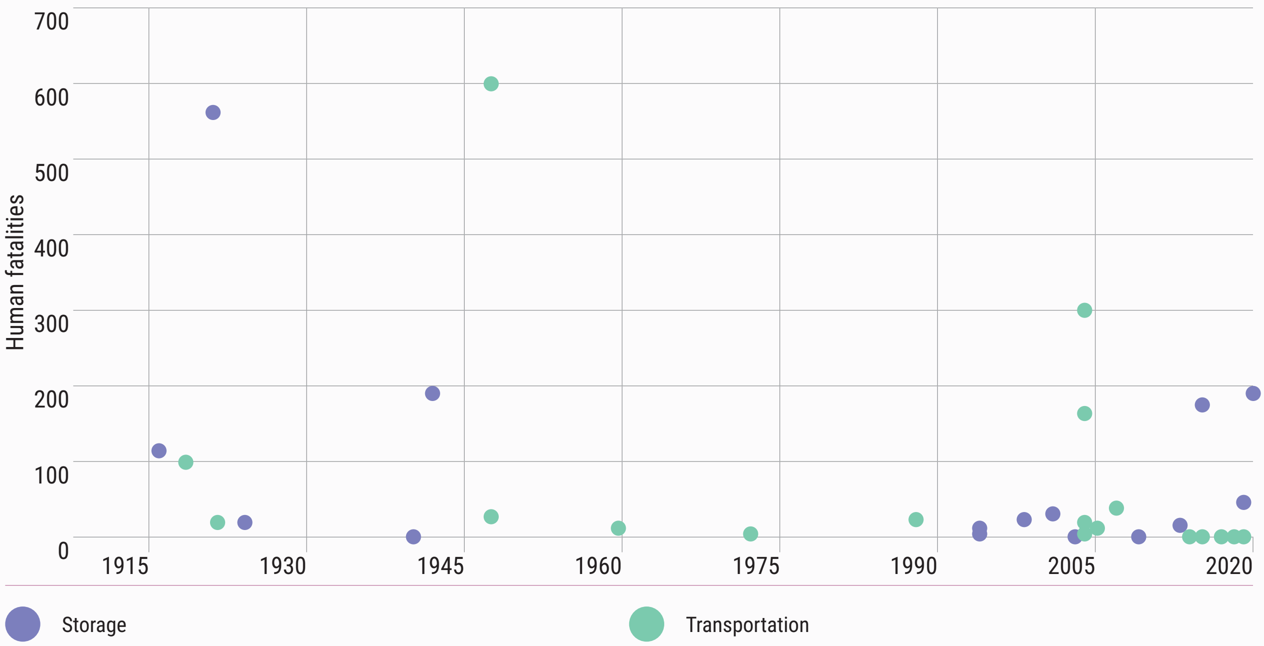
Premature deaths

There are no estimates of global premature deaths due to fertilizers. Existing studies suggest that fertilizers could contribute to a significant number of these deaths annually.

According to estimates by Pozzer *et al*. (2017), a 50 per cent reduction in agricultural emissions could reduce the number of premature deaths by 250,000 per year; assuming no agricultural emissions premature deaths would be reduced by 800,000. It should be noted that on this topic no other publications with global coverage were found. However, a study on maize (corn) production in the United States associated 4,300 premature deaths with reduced air quality due to nitrogen from inorganic fertilizer and manure (Hill *et al*. 2019). According to Anderson *et al*. (2019), about 67,000 deaths per year in 33 Organisation for Economic Co-operation and Development (OECD) and European Union (EU)/European Economic Area (EEA) countries could be due to antimicrobial resistance (AMR). The contribution of manure is not estimated in that study.

Deaths from accidents involving fertilizers have been reported, but they are rare. Dozens of major incidents involving (reactive) nitrogen fertilizers, especially ammonium nitrate, have been documented in different parts of the world (United States Environmental Protection Agency 2015). While guidelines have been developed on the transport, storage and handling of ammonium nitrate fertilizer (Chapter 1.7), accidents resulting in fatalities do occur (Figure 10.2-1). For example, in 2015 an accident in the port city of Tianjin,

Figure 10.2-1 Human fatalities involving ammonium nitrate, 1916-2019. Source of data: Compiled by UNEP



China killed 173 people and injured nearly 800 (Zhao 2016); in 2020 at least 220 people died and many more were injured in an accident in Beirut, Lebanon that left about 300,000 people homeless and destroyed enormous amounts of property. According to authorities, the latter accident was the result of 2,750 tons of ammonium nitrate having been stored improperly for six years in a port warehouse (Guglielmi 2020).

Human health costs

There are no global estimates of the total human health costs of fertilizer use. However, attempts have been made to estimate the costs of pollution by nitrogen and other pollutants, pathogens, and AMR, to all of which fertilizer is a contributor. Despite lack of data, this report presents the few published studies. It should be noted that the data in these studies are subject to much uncertainty.

Several studies have estimated the damage costs to human health of agricultural nitrogen. In the United States, Hill *et al*. (2019) estimated that the air quality-related health costs of using nitrogen fertilizer (inorganic and manure) in maize production could be in the range of United States dollars (USD) 14-64 billion (average USD 39 billion).

For potentially toxic trace elements like cadmium, health costs could be minimal. This is especially true in the case of inorganic fertilizers, as they are used in quantities that are too small to affect human health (Lugon-Moulin *et al*. 2006; Pizzol, Smart and Thomsen 2014). According to Pizzol Smart and Thomsen (2014), the health costs of cadmium in inorganic fertilizer were estimated to average 15.53 euros/year for each square kilometre of Danish agricultural soil to which this fertilizer was applied, while the health costs of cadmium in organic inputs were almost double this amount (28.60 euros/year for sludge and 37.04 euros/year for pig manure). These studies suggest that toxic trace elements in organic inputs can pose a slightly higher risk than those in inorganic fertilizers, but that the risks posed by organic inputs may not be significant in the short term.

In the case of pathogens, the monetary value of health costs could be at least USD 1 billion. For example, the global burden of cystic echinococcosis, a health outcome of helminths, has been estimated to be USD 0.8 billion per year (Budke, Deplazes and Torgerson 2006) and health costs related to foodborne pathogens have been estimated to be about USD 380 million/year (Tegtmeier and Duffy 2004).

The study by Anderson *et al*. (2019) of AMR-related health costs in OECD and EU/European Economic Area (EEA) countries found that, according to OECD models, improved use of antibiotics could reduce deaths from AMR by half and save about 2.3 billion euros. (The contribution of manure was to AMR was not estimated.) Since about 70-80 per cent of antibiotics produced are used in livestock (World Economic Forum 2017), it is possible that a proportion of these costs is due to handling and use of manure. However, according to a study by Miller *et al*. (2019), transmission of AMR to food grown in soil to which animal manure has been applied may be minimal.

10.2.2 Ecosystem services and planetary boundaries

There is no publication presenting total global estimates of ecosystem damage due to nitrogen. However, cost estimates by Sutton *et al*. (2013) of global damage caused by nitrogen include costs to the environment. Regional estimates based on the available literature are presented below. In addition to the monetary value of damage to ecosystem services, the planetary boundary for nitrogen and phosphorus flows is considered to have been exceeded.

Sutton *et al*. (2019) estimated global damage to the coastal aquatic environment by nitrogen and phosphorus, associated with hypoxia, to be about USD 170 billion annually. These costs vary among regions. Studies have estimated the costs of eutrophication in the EU and the United States to be in the billions of dollars. In the United States annual losses due to eutrophication in respect of recreational water usage, waterfront property values, threatened and endangered species recovery efforts, and spending on drinking water were estimated to be USD 2.2 billion by Dodds *et al*. (2009). In the EU in 2008 the costs of eutrophication were estimated by van Grinsven *et al*. (2018) to be 93 billion euros (58 billion euros and 35 billion euros for nitrogen leaching and ammonia deposition, respectively). Since nitrogen and phosphorus both contribute to eutrophication (Chapter 9, Figure 9.3-1), the damage cost of phosphorus to the aquatic environment is probably covered in all these studies.

Little is known about the costs of nutrient losses with regard to ecosystem services such as water regulation and biodiversity. For example, no data were found concerning the impacts of nutrient loads on water regulation services provided by wetlands, although wetlands provide services such as water supply and the control of pollution and flooding (International Water Management Institute 2006). Loss of coastal habitats and coral reefs increases risks from floods and hurricanes to life and property for 100-300 million people (IPBES 2019). In the EU in 2008 the costs of degradation of the terrestrial ecosystem by ammonia deposition was estimated to be 5 billion euros (van Grinsven *et al*. 2018). It has been pointed out by de Graaff *et al*. (2019) that more studies are needed on the links between environmental change, soil biodiversity and ecosystem functioning.

The concept that there are nine planetary boundaries beyond which anthropogenic change will put the Earth system outside a safe operating space for humanity was introduced in 2009 (Rockström *et al*. 2009; Stockholm Resilience Centre 2020). It has been further developed by Steffen *et al*. (2015), Willet *et al*. (2019) and others. The nine planetary boundaries are land-system change, freshwater use, biogeochemical flows, biosphere integrity, climate change, ocean acidification, stratospheric ozone depletion, atmospheric aerosol loading, and novel entities. Nitrogen and phosphorus flows to the biosphere and oceans are considered to be beyond the estimated safe planetary boundary for biochemical flows (Stockholm Resilience Centre 2020). However, it should be noted that the actual positioning of biochemical flows and other boundaries – and how to interpret these boundaries – continues to be debated (Mace *et al*. 2014; Vargas, Willemen and Hein 2018; Willet *et al*. 2019; Pickering and Perrson 2020).

Agricultural production has been identified as a major driver for the exceedance of planetary boundaries, with overfertilization and low nutrient use efficiencies contributing to nutrient losses (Campbell *et al*. 2017). Gerten *et al*. (2020) estimate that half of current global food production depends on planetary boundary transgressions. The key prerequisites identified by the authors for a transformation towards more sustainable production and consumption patterns are spatially redistributed cropland, improved water-nutrient management, food waste reduction and dietary changes.

10.2.3 Total monetary costs of human and environmental damage

Some regional and national studies, and one global study, have attempted to assess the damage costs of nitrogen damage for both the environment and human health.

In the United States, Sobota *et al*. (2015) estimated that potential damage to the environment and human health from nitrogen use in agriculture could be in the range of USD 59-340 billion/year (median USD 157 billion). In the EU-27, damage from agricultural nitrogen was estimated by van Grinsven *et al*. (2013) to be in the range of 35-230 billion euros/year. In China, according to a study on ammonia emissions by Zhang *et al*. (2020), reducing agricultural ammonia emissions could result in environmental and human health benefits of about USD 18-42 billion. Another study in Europe by von Blottnitz *et al*. (2006) estimated that one kilogram of nitrogen fertilizer resulted in damage costs of about 0.3 euros.

Globally, the costs of nitrogen damage associated with ecosystems, climate change and human health could, according to Sutton *et al*. (2013), be in the range of 300-3,000 billion euros (the equivalent of around USD 340-3,400 billion in 2019). However, the authors emphasize that this estimate is largely based on EU estimates (van Grinsven *et al*. 2013) about which there are considerable uncertainties.

Furthermore, there is a lack of data on fertilizers' contribution to global estimates of the costs of nitrogen damage although that contribution could be substantial. Sutton *et al*. (2013) suggested that improving nutrient use efficiency by 20 per cent could reduce damage costs with regard to biodiversity, the climate and humans by about USD 170 billion per year. Furthermore, in the EU study by van Grinsven et al. (2013) agriculture was estimated to contribute about 47 per cent of the damage costs.

Environmental and health costs associated with nutrient pollution are often much greater than the costs of measures to abate these pollutants (Sutton *et al*. 2013), as demonstrated in the following examples. The benefits of a theoretical complete phase-out of ammonia emissions from agriculture in the EU would outweigh the costs of these measures by at least ten times (Giannadaki *et al*. 2018). In China, Zhang *et al*. (2020) estimate that mitigating agricultural ammonia emissions by 38-67 per cent would cost about USD 6-11 billion and that the overall societal benefits would be about USD 18-42 billion. According to a World Water Assessment Programme report (United Nations Educational, Scientific and Cultural Organization [UNESCO] 2017), for every dollar spent on sanitation, the estimated return to society is USD 5.5 and simultaneous recovery of both energy and nutrients from wastewater can be profitable. However, recovering nutrients from wastewater is unlikely to be profitable for the recycling industry (Molinos-Senante *et al*. 2011; Kanter, Zhang and Mauzerall 2014). Options to encourage recycling can include offering subsidies to industry and integrating energy and fertilizer policies.

10.3 Agronomic, economic, health and environmental benefits

10.3.1 Agronomic benefits

Historically, the use of fertilizers, in combination with improved varieties and better management practices, has resulted in increased yields and increased production. For example, cotton yields tripled in West Africa between 1960 and 1985 with increased fertilizer use and better management practices (Pieri 1989, as cited by Bationo and Waswa 2011).

Similarly, the Green Revolution was associated with increased use of fertilizers combined with improved varieties and better management practices. In Asia it resulted in a doubling of cereal production (from 313 million to 650 million tons/year) between 1970 and 1995 (Hazell 2009). Although the contribution of fertilizers to increased yields has not been quantified, it is likely to have been substantial. For example, according to a long-term study by Stewart *et al*. (2005), the average percentage of yields attributable to fertilizer generally ranged from about 40 to 60 per cent in the United States and the United Kingdom and tended to be much higher in the tropics.

10.3.2 Economic benefits

Global data on the economic benefits of fertilizer use are lacking. Furthermore, the available data do not allow such an overview. However, the value of agricultural crop production globally outweighs the value of the fertilizers used. For example, in 2016 agricultural crop production was valued at USD 2.6 trillion (IPBES 2019). If the contribution of fertilizers to yield is about 50 per cent, as reported in the literature (Stewart et al. 2005; Hazell 2009), in 2016 they could have contributed produce worth about USD 1.3 trillion (i.e., 50 per cent of the USD 2.6 trillion estimated by IPBES). These values should, however, be taken with caution.

According to a report by the International Fertilizer Association, in 2018 global revenue from sales of inorganic fertilizers was about USD 151 billion (International Fertilizer Association [IFA] 2020). There are no global estimates of the monetary value of organic inputs (e.g., manure). If the 110 million tons of nitrogen in manure estimated to be left in pasture or applied to land annually (Chapter 7) were replaced with nitrogen from inorganic fertilizers, the cost of inorganic fertilizers, based on the revenue reported by IFA (2020), could be slightly above USD 70 billion dollars. (This estimate is based on the assumption that inorganic fertilizers supply about 110 million tons of nitrogen per year; see Chapter 7, Figure 7.3-5). The actual value of nitrogen in manure could, however, be less than USD 70 billion. For example, according to studies by Rurangwa, Vanlauwe and Giller (2018) and Leip *et al.* (2019), the cost of a kilogram of nitrogen in inorganic fertilizer in Rwanda could be more than double that of a kilogram of nitrogen in manure. Manure also supplies other nutrients (e.g., phosphorus and potassium), but there are no global estimates of the quantities of these nutrients. Overall, there are no global estimates of the total value of fertilizers used in agriculture (i.e., the combined value of inorganic and organic fertilizers). It is not possible to produce such estimates for this report owing to lack of data.

Studies have demonstrated that fertilizer use is mostly economically profitable, but that it can also be unprofitable. In Africa, Asia and Latin America the value of additional yields obtained due to fertilizer use was more than twice the cost of the fertilizer applied in many cereal experiments (Kelly 2005). However, in some cases the cost of fertilizer was more than, or equal to, the value of the additional yield. The rule of thumb is that the increase in produce value must be at least double the fertilizer cost before a farmer will consider fertilizer use (Kelly 2005).

Fertilizer use can have numerous benefits for farmers. For example, in cassava production in Nigeria it was associated with reduced food insecurity, reduced poverty, and improved well-being of rural farmers (Donkor *et al*. 2019). In Ghana fertilizer use was associated with increased household income in rice farming (Martey, Kuwornu and Adjebeng-Danquah 2019). However, while literature quantifying the contribution of such benefits compared with total benefits are lacking, overall, the increase in fertilizer use per unit of land, as well as in total global use over the years, is an indicator that it has economic benefits.

Global studies comparing the economic benefits of using fertilizers (for farmers) with damage costs are lacking. Existing studies suggest that the cost of pollution could either outweigh or be outweighed by the economic benefits of fertilizer use. For example, estimates by van Grinsven *et al*. (2013) suggest that the cost of pollution from nitrogen use in agricultural production in the EU-27 in 2008 could have been greater than the economic benefit (35-230 billion euros/year vs. 20-80 billion euros/year). In China Tang *et al*. (2019) reported that an increase in the net economic value of vegetables due to use of fertilizers (inorganic and organic) outweighed environmental and health costs (i.e., damage to ecosystems and human health and contribution to global warming) by ≥15 times. The benefits increased by about 133,000-222,000 Yuan/ha/year and the damage increased by 6,000-8,000 Yuan/ha/year. However, with an increase in the amount of fertilizer used, the increase in benefits is bound to slow down while damage costs continue to rise.

The question of who pays for pollution damage requires careful consideration. In the case of non-point pollution, identifying polluters can be difficult and expensive (FAO 2018a; FAO 2018b). Passing costs on to polluters provides incentives for sustainable use of fertilizers. However, if the costs are too high, industry and farmers can be pushed out of business. On the other hand, passing costs on to consumers makes food more expensive.

10.3.3 Health

Globally, malnutrition represents the greatest risk factor in regard to the global burden of disease (Global Panel on Agriculture and Food Systems for Nutrition 2016b). The health costs of all forms of malnutrition could be up to USD 3.5 trillion (of which USD 0.5 trillion for overnutrition, i.e., overweight and obesity) (United Nations Children's Fund [UNICEF] 2018).

Undernourishment

Fertilizers have contributed to increased food production globally (Bruulsema *et al*. 2012). Erisman *et al*. (2008) estimated that in 2008 nitrogen fertilizers produced using the Haber-Bosch process were responsible for feeding about 48 per cent of the world population. They concluded that the lives of about half of world population had been made possible through the use of these fertilizers.

Data on fertilizers' global impact on undernourishment is lacking. However, evidence from the Green Revolution demonstrates that they have made a substantial contribution to human health. Hazell (2009) reported that the Green Revolution in Asia resulted in an increase of nearly 30 per cent in the amount of calories available per person despite a 60 per cent population increase between 1970 and 1995.

Today almost 0.8 billion people are undernourished (Peng and Berry 2018), 149 million children are stunted (Development Initiatives 2020), and about 45 per cent of deaths among children under five are associated with undernutrition (WHO 2020). As the global population continues to increase, the number of undernourished people may continue to grow. Seachinger *et al*. (2019) estimated that to feed a projected world population of 10 billion in 2050, calorie production will have to be about 56 per cent more than in 2010. In sub-Saharan Africa, where the population is expected to double by 2050, providing healthy diets to all will require increased fertilizer use (Elrys *et al*. 2020). Overall, responsible use of fertilizers can contribute to reducing undernourishment

Micronutrient deficiencies (hidden hunger)

Globally, over 2 billion people are estimated to suffer from micronutrient deficiencies caused by dietary deficiencies of nutrients and vitamins (FAO *et al*. 2020). The estimate by Peng and Berry (2018) that 33-50 per cent of the world population is micronutrient deficient is consistent with the estimate of 2 billion people in FAO *et al*. (2020) In 2019, 340 million children were estimated to suffer from micronutrient deficiencies.

The micronutrients for which agronomic biofortification has been carried out, or which have been the subject of experiments, include selenium, zinc, iron and iodine. About a billion people suffer from iron deficiency (Global Burden of Disease Study 2013 Collaborators 2015). Zinc deficiency could be affecting 1.1 billion people (Wessells and Brown 2012). In 2002 WHO reported that 1.4 per cent of deaths worldwide (0.8 million) were attributable to zinc deficiency (1.4 per cent in males and 1.5 per cent in females). Attributable DALYs were higher (28 million worldwide), with zinc deficiency accounting for about 2.9 per cent of worldwide loss of healthy life years (WHO 2002). Two decades ago, some 0.5-1 billion people could have been suffering from selenium deficiency (Combs 2001).

Case studies on the health benefits of consuming foods biofortified through fertilizer use are scarce. The only case found was that of the national programme in Finland, where selenium has been added to fertilizers since 1985 to reduce deficiencies in humans (reviewed by Alfthan *et al*. 2015). The authors reported that the concentration of selenium in cereals increased and that dietary intake in 2014 was double the intake in 1985. They argued, however, that the impact of the programme on human health could not be determined due to lack of a selenium deficiency disease and of a reference population.

The benefits of addressing malnutrition can outweigh the costs. Addressing global micronutrient deficiency through supplementation, food biofortification and agronomic biofortification would incur annual costs of about USD 1.2 billion and benefits of about USD 15.3 billion (Global Panel on Agriculture and Food Systems for Nutrition 2016a). Joy *et al*. (2017) reported that agronomic biofortification with zinc has both agronomic and health benefits. They estimated that the yield benefits of fertilizer biofortification were more than 10 times the cost of fertilizer, while DALYs decreased by about 40 per cent and gross returns from reduction in disease burden was at least eight times greater on average than the costs of fertilizer.

Other health benefits

The existing literature suggests that nitrates can have beneficial effects. A systematic literature search by Blekkenhorst *et al*. (2018) concluded there is strong evidence that dietary nitrate (e.g., derived from vegetables) can reduce cardiovascular disease in humans. A narrative review by Wikoff et al. (2018) came to a similar conclusion about the benefits of nitrates in regard to cardiovascular disease. Organic nitrates are also among the commonly prescribed medications for treatment and management of cardiovascular disorders (Adams and Khan 2020). Since nitrogen from fertilizer has been linked to nitrates in, for example, vegetables (Salehzadeh *et al*. 2020), it is likely that nitrogen fertilizers can have a positive effect on cardiovascular disease. However, evidence of the link between nitrates from fertilizer and health benefits is lacking, so that the positive impact remains unknown or undocumented.

10.3.4 Environmental benefits

Soil carbon

Although experiments (Ge, Zhu and Jiang 2018) and meta-analysis of published experimental data (Han *et al*. 2016) have reported that fertilizers can have positive effects on soil carbon, literature concerning the quantification of the impacts of fertilizer on soil carbon is scarce. Baveye, Baveye and Gowdy (2016), who reviewed the evolution of research on soil ecosystem services during the last two decades, reported that scientists have made efforts to quantify soil services but have shown minimal interest in monetary valuation. Still, scientists (Lal 2014; Brady *et al*. 2015) have made efforts to put values on changes in soil carbon. Furthermore, Tang *et al*. (2019) quantified the change in ecosystem services from carbon due to use of fertilizers. Based on a field experiment in China, they reported that the economic value of the regulating services provided by soil carbon showed modest increases with organic inputs (194-333 Yuan/ha/year, or about USD 30-50).

Saving forests

Fertilizer use has contributed, to some extent, to saving forests. According to estimates by Stevenson *et al*. (2013), about 17.9-26.7 million hectares of land under pasture and forests would have been converted to cropland between 1965 and 2004 were it not for the Green Revolution. The avoided loss of ecosystem services provided by forests could have been in the billions of dollars. For example, FAO has estimated that the value of the loss of ecosystem services due to deforestation could be about USD 1,600/ha of forest lost (FAO 2014). This implies that the avoided loss of ecosystem services due to saving of 17.9-26.7 million hectares of pasture and forest land could have been about USD 30-40 billion/year. Furthermore, the avoided loss of carbon emissions could have been substantial. A global study by Burney, Davis and Lobell (2010) on greenhouse gas (GHG) emissions between 1961 and 2005 estimated that yield gains since 1961 resulting from intensification had avoided overall carbon emissions of up to 161 gigatons of carbon (GtC).

10.4 Data gaps and challenges

There are large data gaps with regard to the impacts of fertilizer use. Furthermore, assessments of the global social costs of nutrient pollution are subject to many uncertainties (Sutton *et al*. 2013). In addition, the existing data are not disaggregated by gender, age or fertilizer type (i.e., on organic fertilizers in comparison to inorganic fertilizers).

As pointed out in Chapter 9, there are large data gaps on the environmental effects of fertilizer use and on the impact of fertilizers on human health. This could be one reason why there are very few impact studies. While a key objective of governments is to improve people's health and welfare, their investment priorities may not include monitoring fertilizers' adverse impacts.

Where data exist, it is difficult to compare the values of pollution costs from different studies. Varying assumptions are made, e.g., in monetizing the different species of reactive nitrogen (Kanter, Zhang and Mauzerall 2014). In addition, it is not easy to predict or estimate damage costs as these are influenced by, for example, fertilizer type, management practices and ecosystem characteristics.

For nitrogen the situation is more complex. Costs largely depend on the pathway the nitrogen follows and the different transformations of the nitrogen that occur (Keeler *et al*. 2016). As in this study, a recent systematic review on the health costs of eutrophication by Kouakou and Poder (2019) demonstrates the difficulties of making comparisons among studies or even combining costs reported in different studies.

Using regional data to make global estimates has some drawbacks. According to Sutton *et al*. (2013), the global estimates presented in that report were calculated by extrapolating values estimated for the EU. The authors further explain that the EU estimates were based on citizens' willingness-to-pay in order to reduce health risks, restore damaged ecosystems and reduce GHG emissions, and that such willingness largely depends on income. This demonstrates the need for the collection of region-specific data (i.e., more granular data).

For different forms of nitrogen pollutants, the estimates made depend to some extent on the approach used to arrive at those estimates. For example, Thompson *et al*. (2019) demonstrated that estimates of nitrous oxide emissions can differ in different models. Furthermore, estimates tend to have large uncertainty ranges (Huang *et al*. 2017). This is supported by Keeler et al. (2016), who concluded that nitrogen-related costs depend on where nitrogen moves and the location, vulnerability and preferences of affected populations.

The data gaps highlighted in this chapter are not the only ones which exist. For example, some studies have associated increases in insect pest populations with the use of fertilizers. If these increases do occur, fertilizer use can result in increased use of pesticides. There is also a need to examine leakages along the food chain. Of the 36 per cent of calories produced that are estimated to be fed to livestock, 12 per cent are estimated to reach human beings in the form of animal products (Cassidy *et al*. 2013). About one-third (by weight) of all food produced is lost or wasted (FAO 2011; FAO 2021). While it is important to be aware of the uncertainties of data on food loss and food waste (Lipinski *et al*. 2013; Xue *et al*. 2017), it is crucial to reduce leakages and recycle nutrients in order to meet global sustainability goal

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