



# Nitrogen Fertilizer: Critical Nutrient, Key Farm Input, and Major Environmental Problem

A discussion paper by  
the National Farmers Union

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Canada's NFU is a direct-membership national organization. Founded in 1969, and with roots going back more than a century, the NFU represents thousands of Canadian farm families and farm units from coast to coast, and also enjoys the support of many non-farmer Associate Members. The NFU embodies the principle that all farmers share common problems and that all farmers must come together, and work with non-farmer allies, in order to address those problems. Our organization believes that agriculture should be economically, socially, and environmentally sustainable. Food production should lead to enriched soils, clean water, a more beautiful countryside, adequate and stable farm incomes, jobs for non-farmers, thriving rural communities, healthy natural ecosystems, and Canadian tables arrayed with diverse, delicious, nutritious foods.

The NFU's governance structures are democratic, participatory, and progressive. A farm unit membership gives equal participation rights to all family members over the age of 14. The NFU has leadership positions for youth, women, men, and BIPOC (black, indigenous, and people of colour) representatives. It was the first major farm organization in Canada to elect a woman as President.

To learn more about the NFU, go to our website: [www.nfu.ca](http://www.nfu.ca). **Please join the NFU, as a farm family or farm unit, as a farm youth member, as a farm worker member, or as a non-farmer Associate Member.** The NFU has a place in our organization for every Canadian concerned about our farms and food systems.

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## Preface

This report embraces limits. It is part of an expanding call for an end to endless growth. Limits are a form of wisdom—and a doorway to liberation, sovereignty, and self-determination. If we cannot escape the unceasing imperative of “More! More!”—if that lash is forever on our backs—we cannot steer our own course or decide our own future. The ceaseless drive to endless increase restricts autonomy, worsens inequality, and kindles anxiety.

Limits are critical guardrails that can prevent our civilization from crashing off its path by devastating the biosphere upon which all people and economic activities depend. To deny limits is irresponsible; reckless. On a crowded, depleting, fast-heating Earth, to ignore limits is to risk the ultimate disaster: the destruction of humanity’s future.

This report centres the idea that the endless quest to increase agricultural yields and output by increasing farm input use—especially fertilizers—cannot continue. It points the way to a different model—one in which farmers will be more secure, net incomes will be higher and more stable, and agribusiness corporations will be dethroned as the primary decision-makers and primary beneficiaries within the system. Farmers—for the good of the planet, their communities, their net incomes, and their own futures—must find alternatives to endlessly striving for ever-higher (input-fuelled) yields.<sup>1</sup>

Working to continuously increase crop yields and output usually means increasing input use. (E.g., In Canada, consumption of nitrogen-in-fertilizer<sup>2</sup> has nearly doubled since 2006.) In turn, increasing input use means increasing greenhouse gas (GHG) emissions. Total emissions from agriculture and farm input production rose by one-third between 1990 and 2020, the most recent year for which we have data (see Ch. 3). The primary driver for that overall increase is rising emissions from nitrogen (N) fertilizer production and use. Key to understanding agricultural GHG emissions is this: *The tonnage of emissions coming out of our fields and farms is a direct function of the tonnage of inputs we push in. A continued commitment to increasing yield and output by increasing the use of inputs is a de facto commitment to increasing emissions.* That increase cannot continue: it is incompatible with a livable future and the relatively benign climate upon which agriculture depends. Global emissions must fall to near zero in the next 28 years. Agricultural emissions must fall. Thus, input use must fall. Thus, yield and output cannot continue their steep rise and probably will decline by some small percentage. (Those who react strongly against such ideas are encouraged to read on, to understand why farmers might suggest such a course.)

The reasons for stepping off the yield-maximization treadmill go *far* beyond the environmental. For the sake of their net incomes, farmers have a strong incentive to reflect upon a different future. Currently, by endlessly chasing yields, farmers do two things: 1. They push ever-increasing volumes of products into oft-uneager markets, thus chronically suppressing prices; and 2. Farmers seek to purchase each year higher and higher tonnages of fertilizers, chemicals, etc., creating ever-escalating

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- 1 This is not to imply that farmers should cease striving to farm as well, productively, and carefully as possible or that yield and output will cease to matter. Rather, the idea is that farmers should continue to farm as well as they can *but without ever-increasing input use* and while pursuing *an expanded range of goals*, including margin maximization and harm minimization. This report recentres an *authentic* version of efficiency: one in which farming well actually means doing so while *minimizing* resource use as well as GHG emissions, toxic releases, and depletion of crucial civilizational materials.
  - 2 The term “nitrogen-in-fertilizer” is used to indicate that we are referring to the tonnage of actual nitrogen nutrient in the fertilizer, not the fertilizer compound itself, which can often be, for example, just 46 percent N (urea) or 82 percent (anhydrous ammonia). This report uses “nitrogen-in-fertilizer” when referring to quantities/tonnage and “nitrogen fertilizer” when referring more generally to those fertilizers. Other documents use “fertilizer nitrogen” instead of “nitrogen-in-fertilizer.”

demand for these products and pushing up input prices and corporate profit margins. In effect, farmers are creating too much supply in the markets into which they must sell and too much demand in the input markets in which they buy. The effects on farmers' margins are easily predictable—and very visible in graphs showing shrinking margins over time (e.g., see Figure 16, page 50).

Take fertilizer as an example. One contributing factor to recurring spikes in fertilizer prices (e.g., spikes in 2007/'08 and again in 2021/'22 and perhaps in '23, as well) is that farmers are constantly demanding more fertilizer than the year before. Imagine the reverse: gradually declining fertilizer use and production-facility overcapacity. But, so long as farmers apply themselves to the project of every year demanding more fertilizer than the year before, farmers empower and embolden the companies and contribute to price spikes and company profiteering. Prices are influenced by supply and demand; thus, relentlessly driving up demand will have predictable results—results negative for farmers.

Imagine if, rather than maximizing supply in grain markets and maximizing demand in input markets, farmers supported by governments say: “We will use public policy tools and work collaboratively to plateau our production and even gradually reduce output—perhaps by ten percent over ten years.” What would happen? Grain markets, responding to reduced supply, likely would increase prices. And input makers, facing the prospect of gradual declines in demand for their products and surplus production capacity, would have a hard time holding their prices significantly above efficient costs. Farmers' margins would increase.

“But what of the world's hungry?” agribusiness elites and aligned pundits will ask. Such questions are often insincere and self-serving. The focus of Cargill, Nutrien, Bayer, Yara, JBS, Nestlé, Deere, etc., is not on feeding the hungry. They are largely uninterested in the hungry—in the poor—who have only tiny budgets for the products these companies strive to sell in multi-billion-dollar volumes.

Moreover, bringing adequate nutrition to all who need it is not a matter of upping production and flooding the world with still more grain, vegetable, meat, and dairy tonnage. We already produce enough food to feed billions more people than we are currently feeding. A huge amount of our food is wasted—in Canada perhaps as much as 40 percent and globally perhaps one-third.<sup>3</sup> Another large fraction of our farm product tonnage is denutritionalized: turned into colas, sugary cereals, chips, cookies, instant noodles, prepared meals, and a range of high-sugar and/or high-carbohydrate over-processed foods that, consumed at current rates, bring the opposite of nutrition and health. And much of our farm output is not turned into any kind of food at all. Among the fastest-growing uses for grains and oilseeds are as feedstocks for biofuels for cars and trucks and, soon, vacation jets and ocean shipping. Another large portion of our crops is used as feedgrains, which means turning 5 to 10 grain Calories or 5 to 10 units of grain protein into one Calorie or one unit of animal protein. Though livestock production can be very positive at a certain scale, grain feeding has massively expanded meat and dairy product supplies and consumption—with animal numbers now far beyond levels that are compatible with a livable planetary future. (Humans and our livestock now outweigh all the wild animals on Earth by 32-to-1. See Ch. 6.)

Just as “patriotism is the last refuge of scoundrels,” “feeding the world” is the last refuge of agribusiness profiteers and their confederates who want to maintain an atmosphere of food shortage, low supply, and crisis in order to keep output and input-demand on ever-upward trajectories, even as these systems devise more wasteful end-uses for our expanding agricultural tonnage. Farmers need to step off the yield-and-output treadmill—the *input-use* treadmill. Farmers, citizens, governments,

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3 Martin Gooch, Abdel Felfel, and Nicole Marenick, “Food Waste in Canada,” Value Chain Management Centre, George Morris Centre, 2010, 2, <http://vcm-international.com/wp-content/uploads/2014/01/Food-Waste-in-Canada-November-2010.pdf>; Jenny Gustavsson et al., “Global Food Losses and Food Waste: Extent, Causes and Prevention” (Rome: UN FAO, 2011), v, <http://www.fao.org/3/mb060e/mb060e.pdf>.

and others need to acknowledge and embrace food-system and *planetary limits*. The era of endless growth is ending. Farmers need to work collectively and be supported to find prosperity, security, dignity, and peace-of-mind in a post-growth era. The solution to hunger cannot be ongoing exponential increases in production, extraction, consumption, dissipation, depletion, and emissions.

This report examines a massive environmental and civilizational error: the hyper-nitrification of Earth. In terms of the amount of nitrogen we inject into the biosphere, humans have moved far past the “safe operating limits” for planet Earth—far past “planetary boundaries” (see Ch. 1). Compared to pre-industrial levels, and mostly via fertilizers, humans have *tripled* the amount of nitrogen flowing through terrestrial ecosystems—through fields, grasslands, forests, wetlands, jungles, and tundra (see Ch. 4 and Table 2, page 23).

This report shows that this is an extremely dangerous situation that can be reversed only if we embrace limits—only if we practice intelligent restraint. If we do not scale back, if we do not move our global nitrogen fluxes back within safe limits, if we do not reduce tonnage produced and applied, if we pretend instead that tweaking our nitrogen-use practices can solve the problem: we may make short-term progress—reducing nitrogen use or associated impacts by a few percentage points over the coming years—but the relentlessly upward trends in grain and meat output and associated fertilizer use will soon reverse any such progress, intensify the problem, and leave us even more imperilled.

Endless growth overwhelms efficiency measures and undoes incremental solutions. Emissions and other impacts can go durably downward only if production ceases to go endlessly and steeply upward. And as we escape the merciless drive to every year produce and consume more than the year before, we create breathing space; indeed, space in which to move and in which we can make deliberate choices, space to reimagine our future—for transformation. But the growth imperative and the yield and input treadmills make transformation impossible—they keep us running ever faster just to keep in the game, and deny us the chance to rest and reflect. We need to step away from these implacable and biosphere-shredding systems. As we do, a world of possibilities opens before us.

This report explores how we have transgressed the limits of nitrogen use, and how we can move back within those limits while supporting farmers and their net incomes and helping all to get the nutrition they need.



## Introduction: Nitrogen as key nutrient and critical problem

*Nitrogen is a critical component of the economy, food security, and planetary health.*

—Benjamin Houlton et al., “A World of Cobenefits: Solving the Global Nitrogen Challenge.”<sup>4</sup>

*Without nitrogen there would be no life on Earth: no chlorophyll, no haemoglobin, no plants or animals. While carbon gives the basic skeleton of organic matter, nitrogen is fundamental to life’s functioning and diversity. From amines and amino acids to proteins and DNA, all of them are nitrogen compounds.*

—Mark Sutton et al., “Nitrogen - Grasping the Challenge.”<sup>5</sup>

*In the period 1900–2000, there has been a nearly fourfold population increase (from about 1.6 to 6 billion people), while the increase in agricultural area was approximately 30%, illustrating the three- [to] fourfold yield increase by crops in that period.... This crop yield increase has also been caused by advances in plant breeding and chemical protection by herbicides and pesticides, but it is unthinkable without the nearly 50-fold increase in N fertilizer in that period....*

—Wim de Vries et al., “Assessing Planetary and Regional Nitrogen Boundaries.”<sup>6</sup>

*N is one of the most serious pollutants of the biosphere, seeping into air and water through soluble and volatile forms including nitrate (NO<sub>3</sub>), ammonia (NH<sub>3</sub>), nitrous oxide (N<sub>2</sub>O), and NO<sub>x</sub>. ... Nitrogen is the most important environmental pollutant produced by agriculture....*

—Rezvan Karimi et al., “An Updated Nitrogen Budget for Canadian Agroecosystems.”<sup>7</sup>

*The massive introduction of reactive nitrogen, like the release of carbon dioxide from fossil fuels, also amounts to an immense—and dangerous—geochemical experiment.*

—Vaclav Smil, “Global Population and the Nitrogen Cycle.”<sup>8</sup>

### Why is nitrogen important?

Nitrogen is an atom (seven protons and seven neutrons circled by seven electrons), an element, number seven on the periodic table, located between carbon (six) and oxygen (eight), and highly reactive with many chemical and biological compounds.

Nitrogen plays crucial roles in natural ecosystems, in human food supplies and agricultural systems, and in our economies. As an irreplaceable part of *all* life (plants, animals, fungi, and micro-organisms), its importance cannot be overstated. Nitrogen flows form one of the core biogeochemical cycles on Earth, along with the water, phosphorus, and carbon cycles. Life *requires* nitrogen.

Nitrogen is an essential part of DNA, RNA, and all amino acids—the latter being the building blocks of proteins key to the metabolisms of humans, other animals, plants, and all life. Nitrogen is a major

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4 Benjamin Houlton et al., “A World of Cobenefits: Solving the Global Nitrogen Challenge,” *Earth’s Future* 7, no. 8 (2019): 865.

5 Sutton, M.A. et al., “Nitrogen - Grasping the Challenge. A Manifesto for Science-in-Action through the International Nitrogen Management System,” Summary Report (Edinburgh: Centre for Ecology & Hydrology, 2019), 2.

6 Wim de Vries et al., “Assessing Planetary and Regional Nitrogen Boundaries Related to Food Security and Adverse Environmental Impacts,” *Current Opinion in Environmental Sustainability* 5, no. 3 (2013): 394.

7 Rezvan Karimi et al., “An Updated Nitrogen Budget for Canadian Agroecosystems,” *Agriculture, Ecosystems & Environment* 304 (2020): 1.

8 Vaclav Smil, “Global Population and the Nitrogen Cycle,” *Scientific American* 277, no. 1 (1997): 80–81.

CO<sub>2</sub> = carbon dioxide | CO<sub>2e</sub> = carbon dioxide equivalent | N<sub>2</sub>O = nitrous oxide | CH<sub>4</sub> = methane | NH<sub>3</sub> = ammonia | NO<sub>x</sub> = nitrogen oxides | Mt = million tonnes

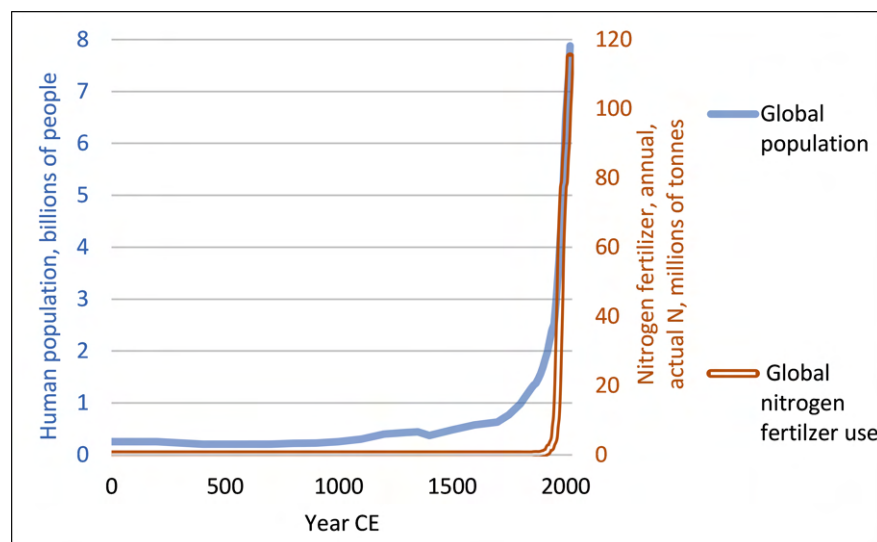


component of chlorophyll in green leaves—therefore key to photosynthesis, the foundation of virtually all Earth’s food chains, natural and agricultural.

Because nitrogen is so essential, changes in its supply can *reshape* ecosystems: altering the mix of organisms and their numbers. Nitrogen scarcity is often the limiting factor in plant growth in natural ecosystems and (at least historically) in farm fields. As such, nitrogen is the most heavily applied agricultural fertilizer. It is an indispensable farm input.

Nitrogen is also a critical economic and civilizational feedstock. The size of our human population and, thus, the size and pace of our global economy are functions of nitrogen flow quantities. Consider: The amount of nitrogen that cycles through the biosphere naturally would not be enough to feed the nearly eight billion humans (and our livestock) that now inhabit Earth. Leading authorities in nitrogen flows calculate that without synthetic nitrogen fertilizer, up to *half* the people alive today could not be fed and therefore could not exist.<sup>9</sup> In his book on the history of synthetic nitrogen production, the University of Manitoba’s Dr. Vaclav Smil calls nitrogen fertilizer “the solution to one of the key limiting factors on the growth of modern civilization.”<sup>10</sup>

Figure 1 shows global human population over the past 2,022 years and also global nitrogen-in-fertilizer consumption.<sup>11</sup> Though the human population began to rise before fertilizer tonnage did so, it is clear from the graph that during the 20<sup>th</sup> century, as human population surpassed 2 or 3 billion, the number of humans and the tonnage of fertilizer became linked. Though we will add nuances below, for now we can say: To feed billions of additional people required billions of tonnes more food and that required tens-of-millions of tonnes of nitrogen fertilizer.



**Figure 1. Human population and nitrogen-in-fertilizer consumption, 0 CE – 2022 CE.**

Sources: Vaclav Smil and International Fertilizer Association (IFA) database.<sup>12</sup>

9 Jan Erisman et al., “How a Century of Ammonia Synthesis Changed the World,” *Nature Geoscience* 1, no. 10 (2008); Vaclav Smil, “Global Population and the Nitrogen Cycle,” *Scientific American* 277, no. 1 (1997). Such estimates rest on assumptions (e.g., levels of food waste or biofuel production). Different assumptions and scenarios would alter the portion of Earth’s inhabitants reliant on synthetic nitrogen, but sustaining current and future populations without some fertilizer would be impossible.

10 Vaclav Smil, *Enriching the Earth: Fritz Haber, Carl Bosch, and the Transformation of World Food Production* (Cambridge, MA: MIT Press, 2004), 228.

11 Throughout, “nitrogen fertilizer” is short for synthetic, factory-made nitrogen fertilizer, and does not include manure, compost, or other organic fertilizers. That said, some of the negative effects ascribed to synthetic fertilizers can also apply to organic fertilizers when those are concentrated in one place, e.g., manure around confined feeding operations. One distinction: manure is usually not counted as an input of *new* nitrogen: rather, it is a recycling flow of previously fixed N.

12 Smil, *Enriching the Earth*, 245–46; International Fertilizer Industry Association, “IFADATA,” n.d., <http://ifadata.fertilizer.org/ucSearch.aspx>.

Without fertilizers, global harvests would be smaller, as would the human population; diets would be very different and livestock numbers far lower. Nations, cities, landscapes, and economies would look radically different—with cities and economies much smaller. In an article by Paul Crutzen (Nobel Prize winner and co-developer of the Anthropocene concept) and Will Steffen (co-developer of the concept of Planetary Boundaries), the authors say that “the Haber-Bosch industrial process to produce ammonia from  $N_2$  in the air made the human population explosion possible. It is amazing to note the importance of this single invention for the evolution on our planet.”<sup>13</sup>

Second only to fossil carbon, synthetic nitrogen has reshaped the world. But it has also damaged it, as we will see next. And though we cannot dispense with nitrogen fertilizer, and though it is of great value to farmers, we must find ways to significantly reduce the tonnage we push into Earth’s biosphere. This implies a broad range of changes in agriculture and all other human systems.

Before we look more deeply at some of the many problems created by the overuse of nitrogen fertilizer, we must stress that in using that fertilizer, farmers are not doing anything “wrong.” Nitrogen fertilizer is an important contributor to human thriving and to many of the benefits we enjoy today. Our levels of nitrogen use are functions, not merely of the choices of individual farmers, but primarily of the core economic, material, and food flows and patterns of our global civilization—driven by concerted corporate and government policies at the highest levels. North American farmers are embedded in a multi-trillion-dollar global system that pushes for ever-higher yields, production, exports, agribusiness profits, etc. In many cases, for an individual farmer to unilaterally renounce fertilizers and step outside the economic logic of that system could be difficult or risky. Instead, the rules of the game must be changed. Incentives must be altered. Market power must be rebalanced. Farmers must be *supported* in *collectively* moving toward production systems that rely much less on factory-made fertilizer and more on natural systems and cycles. We must get less of what we need from industry and more from biology.

Just as climate change cannot be solved by individual consumer actions alone, and coordinated government policy interventions are needed, the same is true for nitrogen fertilizer overuse. Farmers have a key role in solving that problem, but their individual efforts must be coordinated and supported by collective public-policy initiatives and financial support.

Most farmers will continue to use fertilizer, as they should. But the quantity of that use must be reduced: in Canada, in the medium term, rolled back by perhaps one-third—to the tonnage being deployed in the period 2008–10. Nitrogen fertilizer can bring significant net benefits, but only if used in optimal quantities. In the quantities now being deployed planet-wide, the environmental and human-health harms are outstripping benefits (see Ch. 8). To be “for” or “against” nitrogen fertilizer is to misunderstand the issues, but on reading the evidence, it is likely that most farmers, other citizens, and policymakers will be against continuing its massive overuse.

## Why is nitrogen a problem?

Human-produced nitrogen is now a top-three global environmental threat, alongside species extinction and climate change (see Ch. 1).

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13 Paul Crutzen and Will Steffen, “How Long Have We Been in the Anthropocene Era? (2003),” in *Paul J. Crutzen and the Anthropocene: A New Epoch in Earth’s History*, ed. Susanne Benner et al. (Cham, Switzerland: Springer, 2021).

$CO_2$  = carbon dioxide |  $CO_2e$  = carbon dioxide equivalent |  $N_2O$  = nitrous oxide |  $CH_4$  = methane |  $NH_3$  = ammonia |  $NO_x$  = nitrogen oxides | Mt = million tonnes

As noted, nitrogen is a key plant nutrient. Its surplus or scarcity reshapes ecosystems. Considering the central role it plays in planetary systems and cycles, the magnitude of human intervention in the nitrogen cycle is shocking. Compared to pre-industrial levels, and mostly via our fertilizer factories, humans have *tripled* the amount of nitrogen flowing through Earth's terrestrial landscapes—through farm fields, grasslands, wetlands, forests, etc.<sup>14</sup> (see also Ch. 4).

Human-made reactive nitrogen ( $N_r$ )<sup>15</sup> comes from three main sources: 1. Production and use of synthetic fertilizers; 2. Planting of N-fixing crops such as soybeans; and 3. The burning of fossil fuels, which results in reactive nitrogen compounds being created from nitrogen in the air. (Manure is not considered a source of new  $N_r$ : it is a recycling flow.)

Before the 20<sup>th</sup> century, natural flows of nitrogen through terrestrial ecosystems totalled about 90 million tonnes (Mt) per year (see Table 2, page 23). Today, as a result of huge increases in cultivation of nitrogen-fixing crops, fossil fuel combustion, and, predominantly, fertilizer production and use, nitrogen flows through terrestrial ecosystems are three times higher: more than 281 Mt per year. Not surprisingly, this massive intrusion into a core biospheric cycle is causing widespread environmental harm.

Worldwide, nitrogen fertilizer production and use creates more than a billion tonnes of greenhouse gases ( $CO_2e$ ) annually.<sup>16</sup> In Canada, continuously rising fertilizer rates and tonnage are the primary

#### Nitrogen-fixing crops

Crops such as peas, lentils, beans, alfalfa, and clover can fix their own nitrogen out of the air because their roots host special bacteria. Nitrogen-fixing crops can be either solutions or problems. At a certain scale, and if used to replace synthetic N fertilizer and to lower total N flows, nitrogen-fixing crops can improve environmental outcomes and the sustainability of food systems. For example, adding legumes to pastures to replace synthetic fertilizer is a clear win, as can be the adoption of diversified crop rotations that include N-fixing legumes. But at the current scale (e.g., more than 300 million acres of soybeans worldwide with roughly three-quarters of output tonnage going to feed livestock\*), nitrogen-fixing crops are significant contributors to the hyper-nitrification of Earth. N-fixing crops are a lot like fertilizer: beneficial in moderate amounts but harmful when taken to the extent we are currently deploying them. This example reminds us that it is possible to turn any solution into a problem.

\* The main products from soybeans are oil and the “cake” left over after oil extraction. The former is primarily human food and the latter mostly livestock feed. Globally, by weight, livestock consume 77 percent of soybean tonnage, mostly in the form of post-oil-extraction cake. As a percentage of value, livestock feed uses provide two-thirds of the value. See, for example, Walter Fraanje and Tara Garnett, “Soy: Food, Feed, and Land Use Change” (Oxford: Food Climate Research Network, University of Oxford., 2020), pp. 5–8.

- 14 David Fowler et al., “Effects of Global Change during the 21st Century on the Nitrogen Cycle,” *Atmospheric Chemistry and Physics* 15, no. 24 (2015): 13850, 13858. Note that the tripling is a result not just of nitrogen fertilizer use, but also of fossil fuel N, cultivation-induced biological nitrogen fixation, etc. See also David Fowler et al., “The Global Nitrogen Cycle in the Twenty-First Century,” *Philosophical Transactions of the Royal Society* 368, no. 1621 (2013): Figure 1 and Table 2; James Galloway et al., “Nitrogen Cycles: Past, Present, and Future,” *Biogeochemistry* 70, no. 2 (2004): 159; and James Galloway et al., “Transformations of the Nitrogen Cycle: Recent Trends, Questions, and Political Solutions,” *Science* 320 (2008): 889. Note that a 2021 review by Galloway et al. suggests that humanity has already quadrupled natural nitrogen flows. See James Galloway, Albert Bleeker, and Jan Willem Erisman, “The Human Creation and Use of Reactive Nitrogen: A Global and Regional Perspective,” *Annual Review of Environment and Resources* 46, no. 1 (2021): 282.
- 15 Reactive nitrogen ( $N_r$ ) compounds are those that can be easily engaged in chemical reactions, including in plants and bacteria—they are often referred to as “bio-available.”  $N_r$  compounds include ammonia ( $NH_3$ ), ammonium ( $NH_4$ ), nitrate ( $NO_3^-$ ), nitric oxide (NO), nitrous oxide ( $N_2O$ ), and organic compounds such as urea ( $CH_4N_2O$ ), but  $N_r$  does not include the relatively non-reactive atmospheric nitrogen gas ( $N_2$ ) that forms more than three-quarters of Earth's atmosphere.
- 16 International Fertilizer Industry Association, “Fertilizers, Climate Change and Enhancing Agricultural Productivity Sustainability” (Paris: IFA, 2009), 10; Hanqin Tian et al., “A Comprehensive Quantification of Global Nitrous Oxide Sources and Sinks,” *Nature* 586, no. 7828 (2020).

$CO_2$  = carbon dioxide |  $CO_2e$  = carbon dioxide equivalent |  $N_2O$  = nitrous oxide |  $CH_4$  = methane |  $NH_3$  = ammonia |  $NO_x$  = nitrogen oxides | Mt = million tonnes

reasons why agricultural emissions are rising. Nitrous oxide (N<sub>2</sub>O), the main GHG resulting from the use of nitrogen fertilizer, is one of the three main drivers of planetary warming, following carbon dioxide and methane. Kilogram for kilogram, N<sub>2</sub>O has a warming effect approximately 300 times that of CO<sub>2</sub>.<sup>17</sup> Moreover, with an atmospheric residence period of more than a hundred years,<sup>18</sup> N<sub>2</sub>O emitted today will continue to disrupt the climate well into the 22<sup>nd</sup> century.

But the environmental harms from the annual global addition of 100 million tonnes of nitrogen-in-fertilizer go far beyond climate impacts. For example, with the banning of chemicals such as chlorofluorocarbons (CFCs), N<sub>2</sub>O, mostly from fertilizer, is now the leading cause of ozone destruction. To give another example, nitrogen fertilizer applied to fields produces a wide range of by-product compounds that subsequently find their way into surface and groundwater, contributing to a range of environmental impacts including algae blooms in lakes (“eutrophication”) and hundreds of huge “dead zones” in oceans. Fertilizer use acidifies soils and water, driving a range of ecosystem changes. And particulate matter (“smog”)—created largely from nitrogen compounds resulting from fossil fuel combustion, fertilizer use, and other sources—kills millions of people worldwide each year (see Ch. 8). A single atom of reactive nitrogen (N<sub>r</sub>), after production in a fertilizer factory and release from a field, can participate in many of these negative impacts in succession. Experts note that “the same atom of N<sub>r</sub> can cause multiple effects in the atmosphere, in terrestrial ecosystems, in freshwater and marine systems, and on human health. We call this sequence of effects the nitrogen cascade.”<sup>19</sup>

The health, environmental, and economic impacts of nitrogen overuse are explored in Chapter 8. Here, it is sufficient to note the diversity and severity of the negative effects. Although some may find these negative characterizations of nitrogen fertilizer surprising, controversial, or suspicious, that should not be the case. Intuitively, we should expect that if humans take one of the key nutrients for plants, one of the main constituents of life on Earth, one of the most important biogeochemical cycling elements, and use fossil-fuelled industrial factories to multiply the mass that flows through natural and human-managed landscapes, we should expect dramatic, far-reaching consequences. We are literally “changing the world.”

The positive effects of our massive deployment of reactive nitrogen include dramatically expanded harvests, populations, cities, and economies. But the negative effects of multiplying nitrogen flows include severe damages to terrestrial, aquatic, and atmospheric systems, as well as to human health. A moderate quantity of nitrogen nutrient is a life-giving boon, but a hundred-million tonnes per year of nitrogen-in-fertilizer is a toxic planetary overdose.

Experts who have studied the many benefits and harms of nitrogen use conclude that “the net public health consequences of a changing N cycle are largely positive at lower levels, but they eventually peak and then become increasingly negative as our creation and use of fixed N continues to climb.”<sup>20</sup> Nitrogen fertilizer is neither “good” nor “bad”; rather, our choices about its use make it so. The challenge facing farmers, governments, and all humanity is to maximize the benefits of precious fertilizers to food supplies, human health, economies, and ecosystems while minimizing the negative

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17 Global Warming Potential (GWP) allows comparisons of the warming power of different GHGs. GWP is a measure of how much heat will be trapped by the emissions of 1 tonne of a given GHG relative to a tonne of CO<sub>2</sub>. This report uses easier-to-remember round figures for the GWP for nitrous oxide and methane: 300 and 30, respectively. Actual 100-year GWPs for N<sub>2</sub>O and CH<sub>4</sub> are, respectively 265 (IPCC AR5) or 298 (AR4) and 28 (AR5) or 25 (AR4). See Greenhouse Gas Protocol, “Global Warming Potential Values,” February 16, 2016, [https://www.ghgprotocol.org/sites/default/files/ghgp/Global-Warming-Potential-Values%20%28Feb%2016%202016%29\\_1.pdf](https://www.ghgprotocol.org/sites/default/files/ghgp/Global-Warming-Potential-Values%20%28Feb%2016%202016%29_1.pdf).

18 United States Environmental Protection Agency, “Overview of Greenhouse Gases,” Overviews and Factsheets, December 23, 2015, <https://www.epa.gov/ghgemissions/overview-greenhouse-gases>.

19 James N. Galloway et al., “The Nitrogen Cascade,” *BioScience* 53, no. 4 (April 1, 2003): 341.

20 Alan Townsend et al., “Human Health Effects of a Changing Global Nitrogen Cycle,” *Frontiers in Ecology and the Environment* 1, no. 5 (2003): 240.

impacts on same. Currently, we are failing to do so. We are unwise, overzealous, and clumsy in our interventions into Earth's sensitive nitrogen cycle.

This report explores nitrogen overuse and makes the case that credible discussions of sustainability and maintaining a benign, civilization-supporting biosphere must have at their core discussions of ways to reduce humanity's overdependence on synthetic fertilizers. But this report also goes beyond the problems, to examine responses—ways that farmers, policymakers, and others can move forward with food production and sustainability as we ramp down fertilizer use. This report aims to:

1. Increase understanding of nitrogen fertilizer as an environmental and climate problem and to increase concern around this issue *as a way of spurring positive actions and change*;
2. Help farmers understand the greenhouse gases, other emissions, and ecosystem impacts attributable to nitrogen fertilizer production and use;
3. Suggest paths toward reductions in emissions and fertilizer use, including the necessary policies and programs that farmers and elected officials need to pursue to end overdependence and safeguard the biosphere; and
4. Show that reducing dependence on purchased fertility can increase farmers' margins and restrain fertilizer company profit-taking and power.

We critique the current situation in order to create urgency for the project of safeguarding the future.

## 1. A nitrogen crisis?

*Over the past fifty years, humans have used more nitrogen in the environment, largely as fertiliser, than virtually any other element.*

—United Nations Environmental Programme.<sup>21</sup>

*We have a looming crisis, it's a crisis in agriculture, and it's related with nitrogen, and particularly with nitrogen fertilizer. ... I call it a crisis because it really is. ... It's probably going to happen very rapidly; it's probably going to take us quite by surprise.*

—Mario Tenuta, University of Manitoba professor of soil ecology and NSERC/WGRF/ Fertilizer Canada Industrial Research Chair in 4R Nutrient Stewardship.<sup>22</sup>

Our multi-megatonne injection of industrially produced nitrogen into the biosphere is a top-tier threat—a crisis. This assessment is not just the opinion of spoil-sport environmentalists: it reflects the consensus among a growing number of scientists from diverse fields.

In recent years, scientists Will Steffen, Johan Rockström, Wim de Vries, and many others have developed the concepts of “planetary boundaries” and “the safe operating space for humanity.”<sup>23</sup> Their work has been published in respected journals such as *Nature* and *Science*. These scientists look at how far humans have pushed past safe limits in areas such as climate change and ozone depletion, and conclude that there are two domains in which humans have pushed furthest past Earth’s safe operating limits. Many people will correctly guess the first: biodiversity loss. Humans have triggered the fastest extinction event in 65 million years, with species disappearing hundreds of times faster than the long-term, background extinction rate.<sup>24</sup> But few people will guess the second domain where we have pushed farthest past planetary boundaries: the nitrogen cycle (see Figure 2, below). Hyper-nitrification is a top-tier environmental crisis. If we were not consumed with discussions of the climate crisis, we would all be talking about the nitrogen crisis.

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21 United Nations Environment Programme (UNEP), “#fridayfact: More Than Half of Nitrogen Applied to Cropland Is Now Washing into Our Rivers,” UNEP, February 28, 2018, <http://www.unep.org/news-and-stories/story/fridayfact-more-half-nitrogen-applied-cropland-now-washing-our-rivers>.

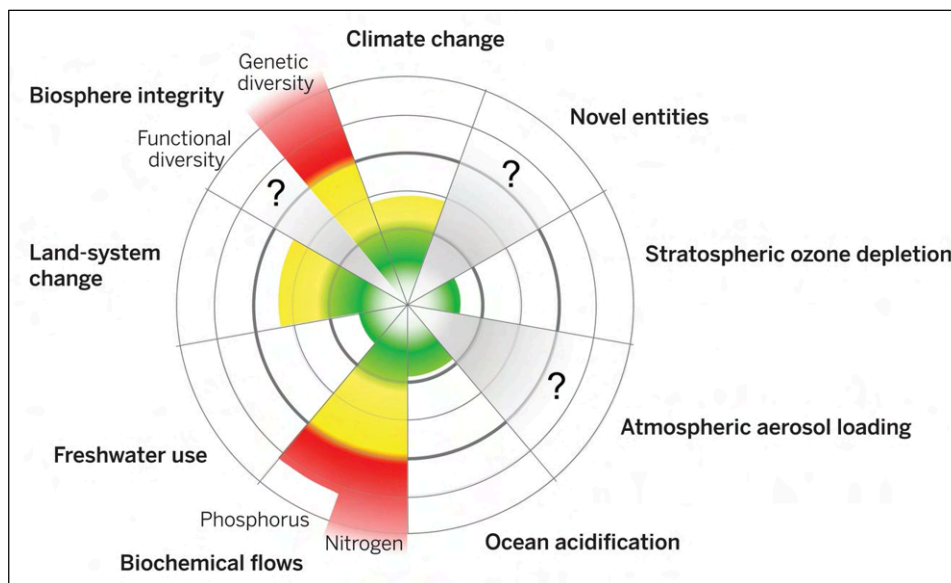
22 Dr. Mario Tenuta - Using the 4Rs to Increase Yields, Video Recording of Presentation (London, ON, 2020), <https://www.youtube.com/watch?v=7-QVWDAQzEQ>.

23 Johan Rockström et al., “Planetary Boundaries: Exploring the Safe Operating Space for Humanity,” *Ecology and Society* 14, no. 2 (2009); Johan Rockström et al., “A Safe Operating Space for Humanity,” *Nature* 461, no. 7263 (2009); Wim de Vries et al., “Assessing Planetary and Regional Nitrogen Boundaries Related to Food Security and Adverse Environmental Impacts,” *Current Opinion in Environmental Sustainability* 5, no. 3 (2013); Will Steffen et al., “Planetary Boundaries: Guiding Human Development on a Changing Planet,” *Science* 347, no. 6223 (2015).

24 Millennium Ecosystem Assessment, *Ecosystems and Human Well-Being: Synthesis* (Washington, DC: Island Press, 2005), 5.

CO<sub>2</sub> = carbon dioxide | CO<sub>2</sub>e = carbon dioxide equivalent | N<sub>2</sub>O = nitrous oxide | CH<sub>4</sub> = methane | NH<sub>3</sub> = ammonia | NO<sub>x</sub> = nitrogen oxides | Mt = million tonnes





**Figure 2. A diagram of human transgressions of planetary boundaries.**

Source: Reproduced from Will Steffen et al., "Planetary Boundaries...", 2015. See footnote below.

In the graphic, the green portion in the centre denotes the safe operating space—the planetary boundary. The yellow portion is a zone of uncertainty—denoting levels of increasing risk. The red portion denotes breaches of planetary boundaries and high risks. In typical scientist understatement, Steffen and his coauthors advise that "Respecting these boundaries would greatly reduce the risk that anthropogenic activities could inadvertently drive the Earth System to a much less hospitable state."<sup>25</sup> Currently, global nitrogen use is more than double the planetary boundary.<sup>26</sup>

This assessment by Rockström, Steffen, de Vries, and others—that we have pushed far past optimal and safe fertilizer tonnage and that hyper-nitrification is now creating very significant risks and damage—is echoed by many others. For example, the 2005 *European Nitrogen Assessment*, written by Mark Sutton and several colleagues, synthesizes contributions from 200 experts.<sup>27</sup> The *Assessment* concludes that environmental and human-health harms from European Union (EU) nitrogen fertilizer use and animal production have risen so high that they probably exceed the economic benefits of fertilizer to farmers. The *Assessment* calculates that "Environmental damage related to N<sub>r</sub> effects from agriculture in the EU-27 was estimated at €20–€150 billion per year. This can be compared with a benefit of N-fertilizer for farmers of €10–€100 billion per year, with considerable uncertainty about long-term N-benefits for crop yield."<sup>28</sup> Though there is uncertainty in these monetary values, note that the magnitude of the harms is in the same general range as (and perhaps larger than) the magnitude of the benefits. There may be no net benefit from EU fertilizer use.

A 2013 article written by several nitrogen experts states: "Many thresholds for human and ecosystem health have been exceeded owing to N<sub>r</sub> pollution, including those for drinking water (nitrates), air quality (smog, particulate matter, ground-level ozone), freshwater eutrophication, biodiversity loss, stratospheric ozone depletion, climate change and coastal ecosystems (dead zones)."<sup>29</sup>

25 Will Steffen et al., "Planetary Boundaries: Guiding Human Development on a Changing Planet," *Science* 347, no. 6223 (2015): 2.

26 Steffen et al., "Planetary Boundaries," Table 1.

27 Mark A. Sutton et al., *European Nitrogen Assessment: Sources, Effects and Policy Perspectives* (Cambridge, UK: Cambridge University Press, 2011), <http://www.nine-esf.org/node/360/ENA-Book.html>.

28 Sutton et al., *European Nitrogen Assessment: Sources, Effects and Policy Perspectives*, xxxi.

29 Jan Erisman et al., "Consequences of Human Modification of the Global Nitrogen Cycle," *Philosophical Transactions of the Royal Society B: Biological Sciences* 368, no. 1621 (2013): 1.

Many people are attempting to draw attention to the nitrogen crisis. There have been several publications in the popular and academic presses.<sup>30</sup> Oxford University hosted a 2015 conference entitled “Tackling the Nitrogen Crisis.”<sup>31</sup> Despite such efforts, discussions of climate change have largely sidelined mention of a nitrogen crisis. The two are, of course, related. As noted above and detailed below, nitrogen fertilizer use creates the greenhouse gas nitrous oxide (N<sub>2</sub>O) and contributes to global warming. But the connection between the two crises goes deeper. A recent journal article poses the question: “Is nitrogen the next carbon?”<sup>32</sup> The article goes on to state that “Just as carbon fueled the Industrial Revolution, nitrogen has fueled an Agricultural Revolution. The use of synthetic nitrogen fertilizers and the cultivation of nitrogen-fixing crops both expanded exponentially during the last century, with most of the increase occurring after 1960.” The implications of these ideas are fourfold:

1. We have used synthetic nitrogen fertilizers in the same ways we have used fossil carbon fuels: to supercharge and supersize human systems;
2. For both carbon fuels and nitrogen fertilizers, that use has now reached biosphere-damaging levels;
3. Just as scrutiny of fossil fuel use has grown in recent decades, scrutiny of nitrogen fertilizer use will grow in the near future; and
4. A consensus has formed that we must cut fossil fuel use, and a similar consensus will emerge for nitrogen fertilizer.

The two foundational human systems are energy and food. Fossil fuels massively expanded the first system; Haber-Bosch nitrogen massively expanded the second. As Robert Socolow noted decades ago, “Managing the food-nitrogen connection is likely to resemble managing the energy-carbon connection.”<sup>33</sup>

Connections between carbon and nitrogen and the climate crisis and the nitrogen crisis are already entering the public and political discourses. A 2015 report by the organization GRAIN called fertilizer companies “The Exxons of Agriculture.”<sup>34</sup>

The intent of the National Farmers Union and the aim of this report is *to prevent nitrogen from becoming the next carbon*. But if humanity is to avoid that outcome, if we are to tackle and reduce the problem before it reaches truly massive proportions and overwhelms us, we must first speak frankly about it. Though effective responses exist, urgency is lacking. This report seeks to help create that urgency: To spur adoption of the many on-farm changes and policy responses that now exist but are largely ignored, even as nitrogen use, emissions, environmental impacts, and human-health harms continue to rise.

30 Fred Pearce, “Can the World Find Solutions to the Nitrogen Pollution Crisis?,” Yale Environment 360, accessed January 14, 2022, <https://e360.yale.edu/features/can-the-world-find-solutions-to-the-nitrogen-pollution-crisis>; Andrew Zaleski, “The Nitrogen Emergency: How to Fix Our Forgotten Environmental Crisis,” New Scientist, accessed January 14, 2022, <https://www.newscientist.com/article/mg25033340-800-the-nitrogen-emergency-how-to-fix-our-forgotten-environmental-crisis/>; “What Can We Learn from the Dutch Nitrogen Crisis?,” Centre for Sustainability, Leiden-Delft-Erasmus Universities, accessed January 14, 2022, <https://www.centre-for-sustainability.nl/news/what-can-we-learn-from-the-dutch-nitrogen-crisis-solutions-for-reforming-the-global-food/>; “Solutions for the Nitrogen Emissions Crisis,” *Metabolic* (blog), accessed January 14, 2022, <https://www.metabolic.nl/news/solutions-for-the-nitrogen-emissions-crisis/>.

31 “World Leading Academics Speak on Tackling the Global Nitrogen Crisis at Symposium,” Somerville College Oxford, October 13, 2015, <https://www.some.ox.ac.uk/news/world-leading-academics-speak-on-tackling-the-global-nitrogen-crisis-at-symposium/>.

32 William Battye, Viney Aneja, and William Schlesinger, “Is Nitrogen the next Carbon?,” *Earth’s Future* 5, no. 9 (2017).

33 Robert Socolow, “Nitrogen Management and the Future of Food: Lessons from the Management of Energy and Carbon,” *Proceedings of the National Academy of Sciences* 96, no. 11 (1999): 6001.

34 GRAIN, “The Exxons of Agriculture” (Barcelona: GRAIN, September 2015).

## 2. Nitrogen fertilizer is a fossil fuel product

*The primary feedstock for producing ammonia is natural gas....*

—The Mosaic (Fertilizer) Company.<sup>35</sup>

*Natural gas is the principal raw material used to manufacture nitrogen.*

—Nutrien Ltd.<sup>36</sup>

Just over a century ago, German chemist Fritz Haber discovered how to synthesize nitrogen-rich ammonia from the atmosphere employing an energy source, a catalyst, and a hydrogen supply. Soon after, German chemist and engineer Carl Bosch commercialized Haber's discovery. Over the past century, Haber-Bosch nitrogen fertilizer has transformed agriculture and the planet.

To simplify: Three things are needed to produce ammonia (NH<sub>3</sub>), the gaseous precursor of almost all other nitrogen fertilizers including granular urea and liquid urea-ammonium nitrate (UAN). To make ammonia, first you need nitrogen (N). That is plentiful: the air we breathe is 78 percent nitrogen gas. But that atmospheric nitrogen is locked up in tightly bonded N<sub>2</sub> pairs, largely unusable by plants and chemically unreactive. Key to making ammonia is cracking open those atmospheric N<sub>2</sub> pairs, a process that requires large amounts of energy.

This brings us to the second thing needed to make ammonia: energy; usually natural gas. Natural gas is combusted to create the high temperatures and pressures needed to split N<sub>2</sub> pairs, to create steam, and to advance the other chemical reactions needed to produce NH<sub>3</sub>.

The third necessary component is hydrogen: the three "H"s in NH<sub>3</sub>. In most cases, that, too, is derived from natural gas, which is mostly methane, or CH<sub>4</sub>—with four hydrogen (H) atoms for every carbon (C). (A by-product of hydrogen synthesis from natural gas is carbon dioxide, CO<sub>2</sub>, from the unused "C" in the CH<sub>4</sub>.) Nutrien, Canada's largest producer of nitrogen fertilizer, tells us that "The majority (more than two-thirds) of our natural gas consumption is as hydrogen feedstock. The remaining one-third is used as fuel to power the ammonia production process."<sup>37</sup>

The preceding, though simplified, itemizes the feedstocks required for nitrogen fertilizer manufacture. Key is natural gas. Natural Resources Canada (NRCan), a federal government department, tells us that "natural gas costs represent between 70 and 90 percent of input costs" for making nitrogen fertilizer and that "the fertilizer industry consumes about 8 percent of the natural gas used in Canada."<sup>38</sup> Though the nitrogen (N) itself is sourced from the air, nitrogen fertilizer is, in effect, a fossil fuel product—so much so that by the time it is applied in the field, the energy embodied in one tonne of nitrogen-in-fertilizer is equal to 1.7 tonnes of gasoline.<sup>39</sup> It will not be surprising, therefore, when, in the next chapter, we detail the large GHG emissions from nitrogen production and use.

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35 The Mosaic Company, "2020 Annual Report" (Tampa: Mosaic, 2021), <https://www.mosaicco.com/fileLibrary/publicFiles/0-2020-Annual-Report.pdf>.

36 Nutrien Ltd., "Form 51-102F4: Business Acquisition Report" (Securities and Exchange Commission), accessed June 19, 2022, <https://www.sec.gov/Archives/edgar/data/1725964/000119312518058412/d492806dex992.htm>.

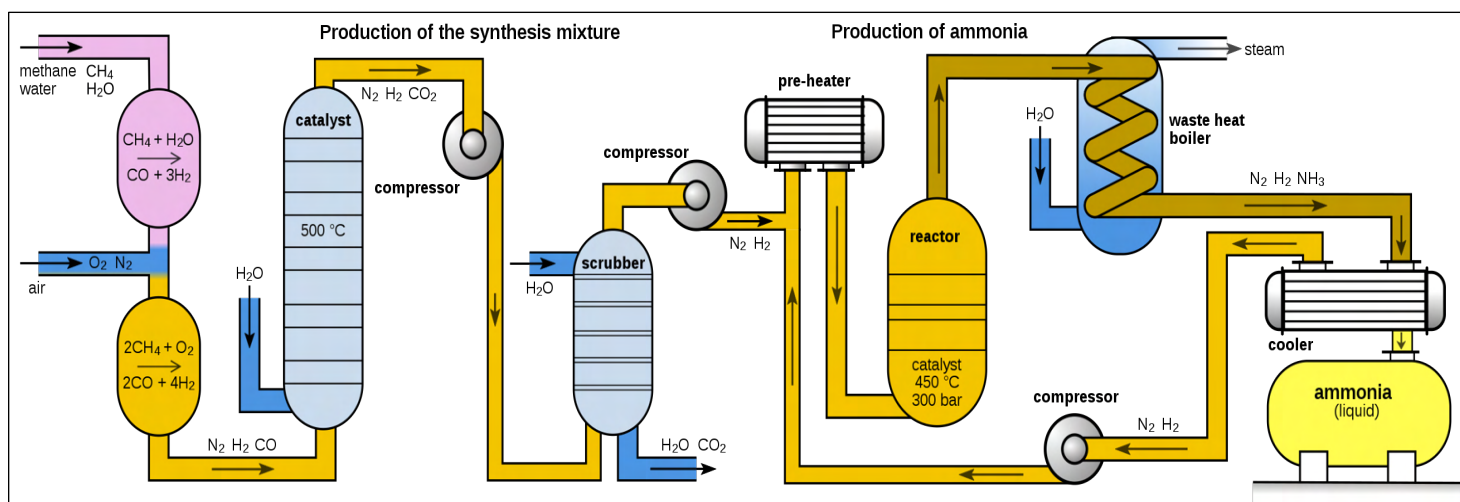
37 Nutrien, "2020 Environmental, Social and Governance (ESG) Report" (Saskatoon: Nutrien, 2020), 14.

38 Natural Resources Canada and Canadian Fertilizer Institute, "Canadian Ammonia Producers: Benchmarking Energy Efficiency and Carbon Dioxide Emissions" (Ottawa: NRCan, 2008), 3.

39 Clark Gellings and Kelly Parmenter, "Energy Efficiency in Fertilizer Production and Use," in *Knowledge for Sustainable Development—An Insight into the Encyclopedia of Life Support Systems*, ed. Clark Gellings and Kornelis Blok, Efficient Use

Nitrogen fertilizer is a fossil fuel product in a deeper sense as well: it serves as an *energy carrier* by which we transfer fossil-fuel energy into our food-energy supply. Though we usually encounter the unit “Calorie” in relation to food, Calories can be used to measure all energy sources: biological, fossil fuel, etc.<sup>40</sup> Via the intermediary of nitrogen fertilizer, we transform fossil fuel Calories from the ground into crops in our fields and on into food Calories on our plates and into people on our streets. Via fertilizer, we turn hydrocarbons into carbohydrates into us.

Figure 3 shows the nitrogen/ammonia production process. Note that the input in the upper left, “methane CH<sub>4</sub>,” is natural gas. Note the output, centre bottom, of CO<sub>2</sub>. While some of that CO<sub>2</sub> is captured and used to make granular urea fertilizer, (NH<sub>2</sub>)<sub>2</sub>CO, and some is now captured and used for enhanced oil recovery,<sup>41</sup> in most fertilizer factories the bulk is vented to the atmosphere.<sup>42</sup>



**Figure 3. A schematic diagram of a generic Haber-Bosch ammonia production facility.**

Source: Wikipedia commons, <https://commons.wikimedia.org/wiki/File:Haber-Bosch-En.svg> .

and Conservation of Energy, Part of the Encyclopedia of Life Support Systems (EOLSS) (Oxford: UNESCO and EOLSS Publishers, 2004), Table 2, <http://www.eolss.net/ebooks/sample%20chapters/c08/e3-18-04-03.pdf>.

40 Capital “C” Calories or kilocalories—the units encountered most often in relation to food energy—are an all-purpose measure of energy content, equal to the amount of energy needed to raise the temperature of one kilogram of water by one degree Celsius. Though humans consume an average of about 2,400 Calories daily as food (as “endosomatic” energy, with “endo” meaning “inside” and “soma” meaning “body”), in highly mechanized, energy-intensive regions, the machines and systems around us utilize about 100 times as much: in Canada, for example, about 230,000 Calories per person per day as “exosomatic” energy. In terms of actual work output, the Caloric energy we take into our bodies is multiplied a hundredfold by the Caloric energy we feed into our machines. Huge quantities of Calories are fed into fertilizer factories—more than one quadrillion Calories per year.

41 “Exciting Project Reduces Emissions at Redwater,” Nutrien, accessed July 16, 2022, <https://www.nutrien.com/what-we-do/stories/exciting-project-reduces-emissions-redwater>.

42 Natural Resources Canada and Canadian Fertilizer Institute, “Canadian Ammonia Producers: Benchmarking Energy Efficiency....”

### 3. Nitrogen fertilizer and greenhouse gas emissions

*Global food system emissions could preclude achieving the 1.5° and 2°C climate change targets.*

—Michael Clark et al. 2020.<sup>43</sup>

*The recent growth in N<sub>2</sub>O emissions exceeds some of the highest projected emission scenarios.*

—Hanqin Tian et al., “A Comprehensive Quantification of Global Nitrous Oxide Sources ....”<sup>44</sup>

Nitrogen fertilizer is unique among all human products and processes in that it is a major source of *all three* of the main greenhouse gases: nitrous oxide (N<sub>2</sub>O), in its use; carbon dioxide (CO<sub>2</sub>), in its production; and methane (CH<sub>4</sub>), from its natural gas feedstock (from venting and leaks during natural gas production, processing, and pipeline transport).

In Canada, nitrogen fertilizer production and use accounts for 27 percent of GHG emissions from agriculture and the production of farm inputs.<sup>45</sup> Most of that amount is made up of N<sub>2</sub>O, a greenhouse gas that, when it comes to trapping heat, is about 300 times more powerful than CO<sub>2</sub>. A continuing rise in Canadian tonnage of nitrogen-in-fertilizer (it has nearly doubled over the past 15 years<sup>46</sup>) is the primary reason that agricultural emissions in this country are rising. Significant reductions in economy-wide emissions by 2030 and attaining near-zero emissions by 2050 will require significant reductions in emissions from the production and use of nitrogen fertilizer. The upward trend in those emissions clashes with the reductions needed throughout the Canadian economy—reductions repeatedly committed to by federal and provincial governments; emission reductions critical to keeping global temperature increases below dangerous levels.

#### Five types of nitrogen-fertilizer-related emissions

Nitrogen fertilizer production and use creates five main categories of emissions:

1. Nitrous oxide (N<sub>2</sub>O) from farm fields as a result of application/use (both direct and indirect emissions);
2. Carbon dioxide (CO<sub>2</sub>) emitted from fields as a result of the use of granular urea, liquid urea-ammonium nitrate (UAN), and other carbon-containing nitrogen fertilizers;
3. CO<sub>2</sub> from fertilizer factories as a result of fossil fuel combustion and from hydrogen synthesis from methane (CO<sub>2</sub> is a by-product of hydrogen production from CH<sub>4</sub>; see Figure 3, page 14.);
4. Methane (CH<sub>4</sub>) and CO<sub>2</sub> from the upstream natural gas supply (CO<sub>2</sub> from industrial machinery and CH<sub>4</sub> from venting and leaks in production and pipeline transport); and
5. CO<sub>2</sub> from transport of nitrogen fertilizers to distribution hubs and onward to farms.

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43 Michael Clark et al., “Global Food System Emissions Could Preclude Achieving the 1.5° and 2°C Climate Change Targets,” *Science* 370, no. 6517 (2020).

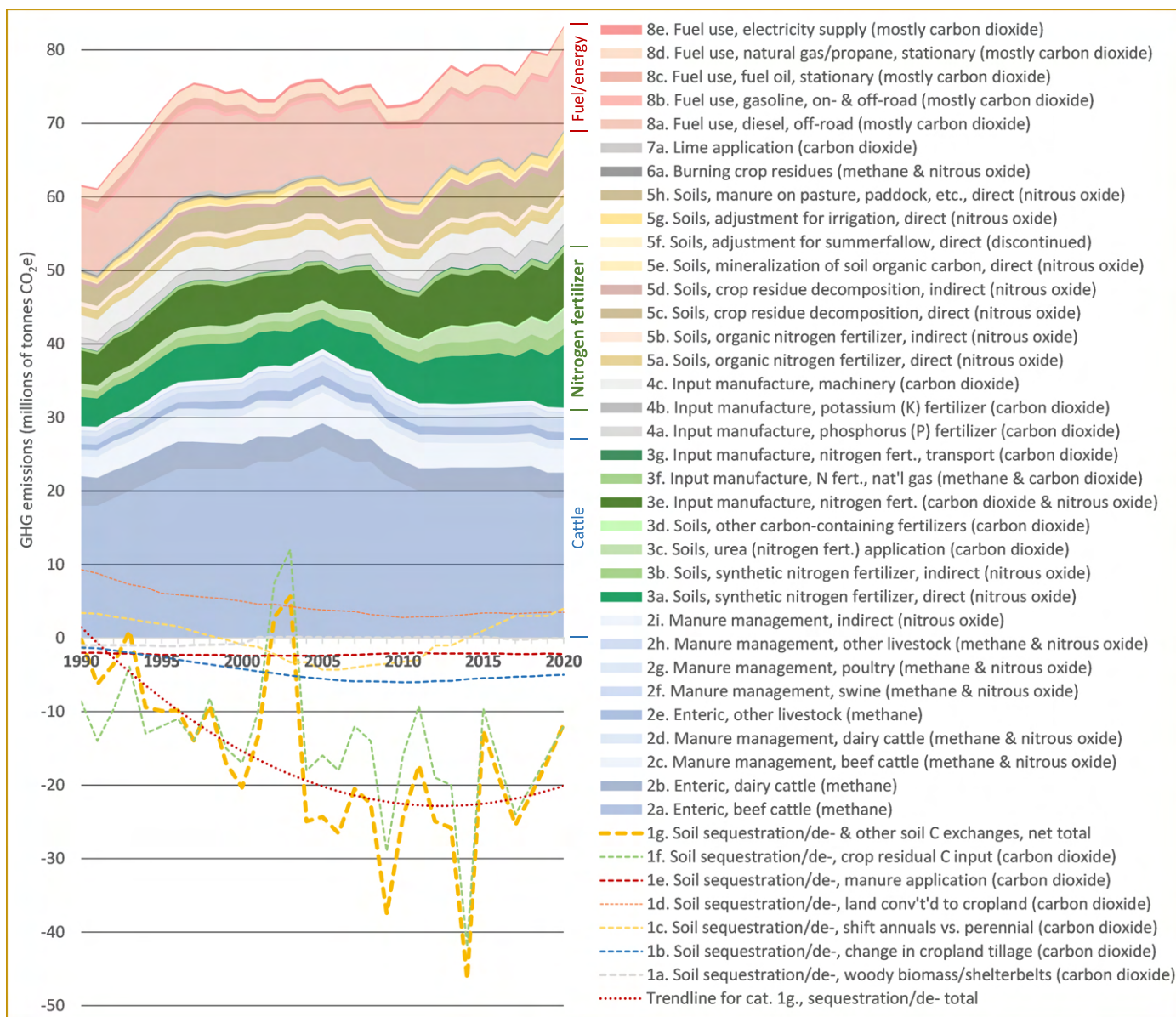
44 Tian et al., “A Comprehensive Quantification of Global Nitrous Oxide Sources and Sinks,” 248.

45 Darrin Qualman and National Farmers Union, “Agricultural Greenhouse Gas Emissions in Canada: A New, Comprehensive Assessment,” Second Edition (Saskatoon: NFU, 2022), <https://www.nfu.ca/wp-content/uploads/2022/06/Comprehensive-Ag-GHG-Emissions-EN-2nd-Ed.pdf>.

46 Statistics Canada Tables 32-10-0039-01 and 32-10-0274-01.



The NFU's June 2022 report *Agricultural Greenhouse Gas Emissions in Canada, Second Edition*, provides details on fertilizer-related emissions.<sup>47</sup> Figure 4 is adapted from that report and shows Canadian agricultural emissions, with those from nitrogen fertilizer production and use highlighted in shades of green. Following the graph is an explanation of each category, beginning from the bottom.



**Figure 4. Canadian agricultural GHG emissions, highlighting fertilizer-related emissions, 1990 – 2020.**

Sources: Produced by the NFU with data from ECCC NIR and CRF Tables, ECCC custom tabulations, Dyer et al., etc. For detailed sources, see the NFU report: *Agricultural Greenhouse Gas Emissions in Canada, Second Edition*.

**Category 3a. Nitrous oxide from nitrogen fertilizer use, direct.** Beginning at the bottom of the green bands in Figure 4 we see the largest component of nitrogen-related emissions: direct emission from soils as a result of fertilizer application. Once fertilizer is in the soil, microorganisms begin turning some of the nitrogen into nitrous oxide (N<sub>2</sub>O). In 2020, these emissions totalled 8.5 Mt CO<sub>2</sub>e per year.

Direct N<sub>2</sub>O emissions from soils in individual fields can be erratic: low for long periods then spiking when soils are saturated with water (“anaerobic”) during spring snowmelt or intense rain events. Also,

47 Qualman and National Farmers Union, “Agricultural Greenhouse Gas Emissions in Canada....2nd Ed.”



fertilizer-related N<sub>2</sub>O emissions from soils might not be linear but rather exponential, e.g., increasing the fertilizer rate by 10 percent might increase emissions by more than 10 percent.<sup>48</sup> The good news is that the converse can be true: Reducing rates by, say, 10 percent can *reduce* emissions by more than 10 percent. Chapter 13 examines effective emission-reduction measures, including the benefits of using the “right rate.”

**Category 3b. Nitrous oxide from nitrogen fertilizer use, indirect.** Putting fertilizer into soils also releases other compounds that are not GHGs, compounds such as ammonia (NH<sub>3</sub>), nitrate (NO<sub>3</sub><sup>-</sup>), and nitrogen oxides (NO<sub>x</sub>). A portion of those compounds move through the air (volatilization) or water (runoff into surface waters or leaching into groundwater), end up far outside the field, and later undergo reactions that create N<sub>2</sub>O and warm the planet. These are “indirect” GHG emissions in that the actual GHGs are released far away from the field and later in time. In some cases, such as leaching, N<sub>2</sub>O production may be separated from fertilizer application by many kilometres and by years or even decades.<sup>49</sup> These indirect emissions are shown in Figure 4 by the lighter green band, second from the bottom of the green bands. Indirect emissions are equal to about one-quarter of direct emissions.

**Categories 3c and 3d. Carbon dioxide from urea and other carbon-containing fertilizers.** Nitrogen fertilizer production begins with the creation of ammonia gas, NH<sub>3</sub>. This can be used directly as a fertilizer—knifed into the soil with special farm equipment. Many farmers, however, prefer to apply solid, granular fertilizers such as urea or the liquid fertilizer urea-ammonium nitrate (UAN). Both contain carbon and those fertilizers release it when put into the soil. In Figure 4, see the light-green bands, third and fourth from the bottom.

**Category 3e. Emissions from fertilizer production facilities.** When fertilizer factories make NH<sub>3</sub>, they emit CO<sub>2</sub> from combustion and from hydrogen extraction from natural gas. Some of that CO<sub>2</sub> is captured to make urea (in Canada, about 40 percent<sup>50</sup>), and some is now captured using carbon capture utilization and storage technology (CCUS), but most is vented, creating large emissions. E.g., Manitoba’s largest single source of GHG emissions is the Koch Fertilizers nitrogen plant at Brandon.<sup>51</sup>

**Category 3f. Methane (and carbon dioxide) from upstream natural gas production.** Natural gas is predominantly methane (CH<sub>4</sub>), a GHG approximately 30 times more powerful than CO<sub>2</sub> in terms of driving climate warming. Natural gas is also the primary feedstock for nitrogen fertilizer production. When natural gas is produced and transported, a significant portion leaks to the atmosphere. Because CH<sub>4</sub> has a much higher warming potential than CO<sub>2</sub>, a quantity of natural gas that leaks has a greater effect than the same quantity burned and turned into CO<sub>2</sub>. In addition to methane from natural gas production and transport, there is also CO<sub>2</sub>: from drilling machinery, pumps, processing plants, etc.

**Category 3g. Emissions from fertilizer transport.** Nitrogen fertilizer has to be transported by trains or trucks from fertilizer factories to distribution and sales centres then onward to farms.

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48 Iurii Shcherbak, Neville Millar, and G. Philip Robertson, “Global Metaanalysis of the Nonlinear Response of Soil Nitrous Oxide (N<sub>2</sub>O) Emissions to Fertilizer Nitrogen,” *Proceedings of the National Academy of Sciences* 111, no. 25 (2014); J.P. Hoben et al., “Nonlinear Nitrous Oxide (N<sub>2</sub>O) Response to Nitrogen Fertilizer in on-Farm Corn Crops of the US Midwest,” *Global Change Biology* 17, no. 2 (2011); Yu Jiang et al., “Nonlinear Response of Soil Ammonia Emissions to Fertilizer Nitrogen,” *Biology and Fertility of Soils* 53, no. 3 (2017); Dong-Gill Kim, Guillermo Hernandez-Ramirez, and Donna Giltrap, “Linear and Nonlinear Dependency of Direct Nitrous Oxide Emissions on Fertilizer Nitrogen Input: A Meta-Analysis,” *Agriculture, Ecosystems & Environment* 168 (2013).

49 Mathieu Sebilo et al., “Long-Term Fate of Nitrate Fertilizer in Agricultural Soils,” *Proceedings of the National Academy of Sciences* 110, no. 45 (2013).

50 Natural Resources Canada and Canadian Fertilizer Institute, “Canadian Ammonia Producers: Benchmarking Energy Efficiency....”

51 Environment and Climate Change Canada, “Greenhouse Gas Emissions from Large Facilities,” website and database, accessed January 6, 2022, <https://www.canada.ca/en/environment-climate-change/services/environmental-indicators/greenhouse-gas-emissions/large-facilities.html>.

## Total emissions from nitrogen fertilizer production and use

In Canada in 2020 (the most recent year for which data is available), emissions from nitrogen fertilizer production and use totalled 22.2 Mt CO<sub>2</sub>e per year, more than double 1990 levels. Emissions from nitrogen fertilizer production and use make up about 27 percent of total agricultural emissions.

As a global average (and omitting CH<sub>4</sub> from the natural gas supply), Menegat et al. found that GHG emissions equalled 10.5 tonnes CO<sub>2</sub>e per tonne of actual N nutrient produced, transported, and applied.<sup>52</sup> This is the “GHG intensity” for nitrogen-in-fertilizer. For Canada, Menegat et al. calculated 11.7 tonnes CO<sub>2</sub>e per tonne of actual N nutrient. For comparison, the NFU’s derived coefficient for production and use of nitrogen-in-fertilizer (our GHG intensity) was just 7.66 tonnes CO<sub>2</sub>e per tonne of fertilizer N, significantly lower than most published sources, indicating that our assumptions and values are conservative. Using other published values or different assumptions, our total could be 50 percent higher.

Key is this: For every tonne of nitrogen nutrient applied in fertilizer, between 7 and 12 tonnes of GHGs (CO<sub>2</sub>e) are released. The primary impediment to stabilizing and reducing emissions from Canadian agriculture is the relentless increase in emissions related to nitrogen fertilizer.

We must acknowledge that nitrogen compounds and their actions in the biosphere and atmosphere have both warming and cooling effects, the latter including particulate matter in smog causing shading and reflection of sunlight, and nitrogen potentially facilitating increased rates of soil carbon sequestration. Some analysts even suggest that cooling effects of nitrogen fertilizer can approach the scale of the warming effects. This latter contention is incorrect because it omits the large emissions from nitrogen fertilizer production, natural gas production, etc. It also omits emissions from livestock systems—emissions that can perhaps be largely attributed to nitrogen fertilizer, as we will detail below. Finally, it also omits the fact (though many analysts note this) that most cooling effects (e.g., smog) are short-duration, while warming effects of N<sub>2</sub>O and CO<sub>2</sub> will continue for a century (N<sub>2</sub>O) or several (CO<sub>2</sub>).

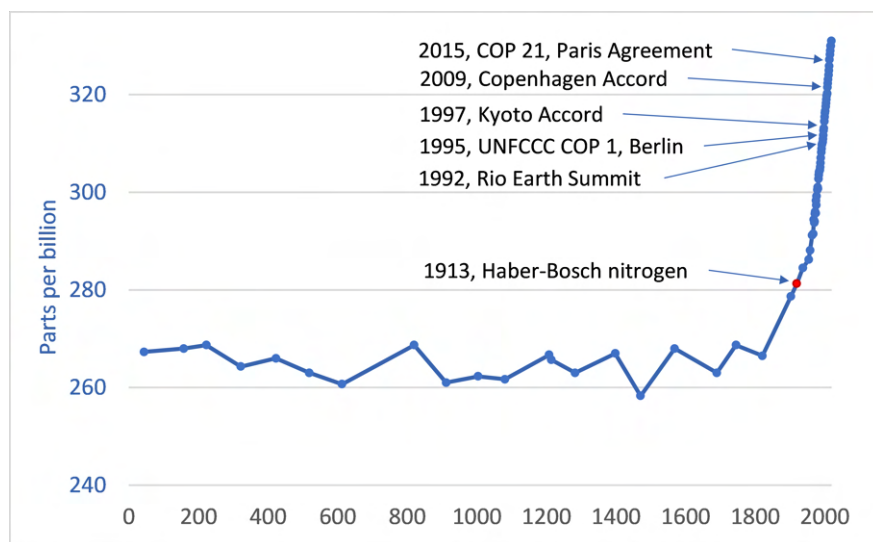
## Nitrogen fertilizer and GHG emissions: The long-term global picture

Figure 5, below, shows the rise in atmospheric N<sub>2</sub>O concentrations and highlights a few of the many global agreements to reduce GHG emissions and stabilize atmospheric concentrations. Synthetic fertilizer use is not the only driver of increasing N<sub>2</sub>O concentrations; another contributor is manure. Indeed, it is emissions from manure that began pushing up atmospheric N<sub>2</sub>O concentrations in the 1800s, before the development of Haber-Bosch nitrogen technologies.<sup>53</sup> That said, conceptually separating manure emissions from those of synthetic fertilizer use is now hard, because were it not for fertilizer, global and Canadian livestock numbers and manure volumes would be *far* lower (see Ch. 6). Hence, we can think of current high rates of manure-related N<sub>2</sub>O emissions as another downstream effect of increasing nitrogen fertilizer production and use. This is not just a vague or metaphoric idea. The actual N atoms in the N<sub>2</sub>O emitted by manure increasingly come from N in fertilizer and from fertilizer factories. The same is true of the N in the N<sub>2</sub>O emitted from human

52 Stefano Menegat, Alicia Ledo, and Reyes Tirado, “Greenhouse Gas Emissions from Global Production and Use of Nitrogen Synthetic Fertilisers in Agriculture,” *Scientific Reports* 12, no. 1 (August 2022): Table 1.

53 Eric Davidson, “The Contribution of Manure and Fertilizer Nitrogen to Atmospheric Nitrous Oxide since 1860,” *Nature Geoscience* 2, no. 9 (2009).

sewage and biosolids. The bulk of the N atoms in North American  $N_2O$  emissions could be thought of as sporting tiny Nutrien, Yara, CF Industries, or Koch logos.



**Figure 5. Global atmospheric nitrous oxide concentrations, 0 CE – 2020 CE.**

Sources: United States Environmental Protection Agency (US EPA).<sup>54</sup>

Figure 5 shows that, for nitrogen fertilizer and nitrous oxide emissions, talk of sustainability and emissions reduction is false and perhaps intentionally misleading.

Finally, and perhaps most troubling, scientists warn that a warming planet will increase the activity of microbes that drive the production and release of  $N_2O$ .<sup>55</sup> In a (very negative) positive-feedback loop,  $N_2O$  will make the world hotter, and a hotter world will accelerate emissions of  $N_2O$ .

54 US EPA, "Climate Change Indicators: Atmospheric Concentrations of Greenhouse Gases," <https://www.epa.gov/climate-indicators/climate-change-indicators-atmospheric-concentrations-greenhouse-gases>. EPA data merges several sources incl. ice cores from Antarctica (Schilt et al.); Antarctica (Battle et al.); Cape Grim, Australia (CSIRO); and South Pole, Barrow, and Mauna Loa (NOAA).

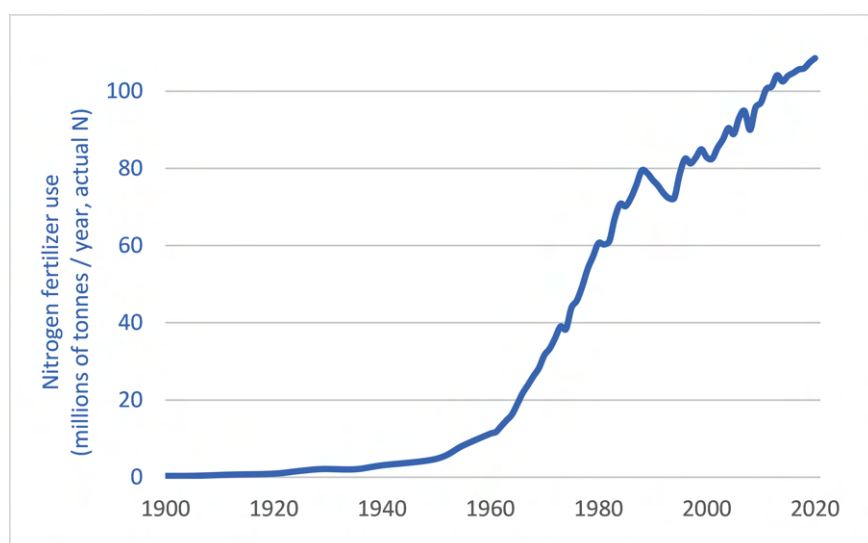
55 Tian et al., "A Comprehensive Quantification of Global Nitrous Oxide Sources and Sinks," 250; Timothy J. Griffis et al., "Nitrous Oxide Emissions Are Enhanced in a Warmer and Wetter World," *Proceedings of the National Academy of Sciences of the United States of America* 114, no. 45 (2017); Keith Smith, "The Potential for Feedback Effects Induced by Global Warming on Emissions of Nitrous Oxide by Soils," *Global Change Biology* 3, no. 4 (1997).

## 4. Global and Canadian nitrogen fertilizer use: Past, present, and future

*In just one lifetime, humanity has indeed developed a profound chemical dependence.*

—Vaclav Smil, “Global Population and the Nitrogen Cycle.”<sup>56</sup>

Figure 1 (page 5) shows global nitrogen-in-fertilizer consumption over the past 2,020 years. Figure 6, below, zooms in on the past 120 years. Note the continuing rise—a doubling over the past 45 years.



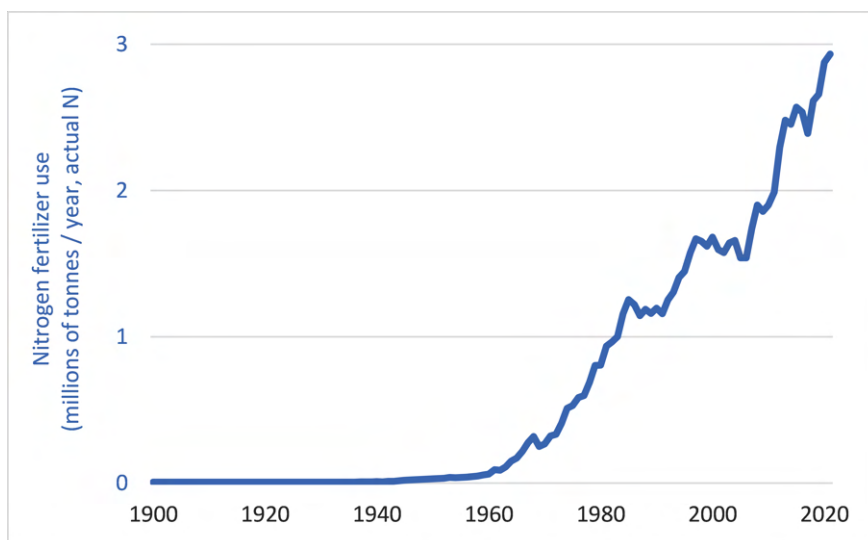
**Figure 6. Global nitrogen-in-fertilizer consumption, 1900 – 2020.**

Sources: Smil and IFA.<sup>57</sup>

Figure 7, next page, shows Canadian nitrogen-in-fertilizer consumptions over the past twelve decades. Tonnage has nearly doubled since 2006 and has quadrupled since 1978.

<sup>56</sup> Smil, “Global Population and the Nitrogen Cycle,” 81.

<sup>57</sup> Vaclav Smil, *Enriching the Earth: Fritz Haber, Carl Bosch, and the Transformation of World Food Production* (Cambridge, MA: MIT Press, 2004), pp. 240 and 245, Appendices F & L; International Fertilizer Industry Association (IFA), “IFADATA,” accessed August 22, 2021, <http://ifadata.fertilizer.org/ucSearch.aspx>.



**Figure 7. Canadian nitrogen-in-fertilizer consumption, 1900 – 2021.**

Sources: Statistics Canada; Korol and Rattray; and Dominion Bureau of Statistics.<sup>58</sup>

Several factors have contributed to increased nitrogen fertilizer use in Canada, including the move from summerfallow to continuous cropping (thus adding more cropped acres) and a larger area of fertilizer-hungry crops such as corn and canola.<sup>59</sup> The primary factor, however, is simply a general trend, primarily in the Prairie region, to apply higher rates of fertilizer each year to each acre.

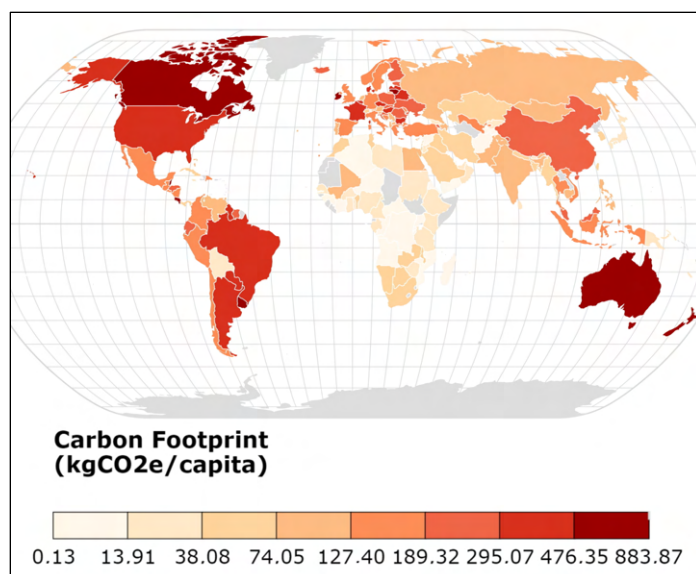
Canadian fertilizer use is high not only relative to the past; it is high relative to other nations. In 2021, Canada was the world's eighth-largest consumer of nitrogen-in-fertilizer.<sup>60</sup> Many factors contribute to this high level, including our large expanses of cropland. Nonetheless, the high overall use in our country is noteworthy.

Figure 8, below, depicts *per-capita* GHG emissions from nitrogen fertilizer use in several nations. Canada's levels are among the highest. Again, this is not unexpected: a function of our low population, our large land base, and our focus on maximizing yields and exports. Nonetheless, we must acknowledge that per-person fertilizer-related emissions here are higher than those in nearly every other nation in the world. If the planet is going to achieve near-zero emissions by 2050, and if global nitrogen fertilizer use must fall, Canadian per-capita emissions from fertilizer production and use will almost certainly have to decline significantly. For the sake of farmers and our net incomes, we must incorporate that reality into our planning as soon as possible. Unlike the 20<sup>th</sup> century, as we move through the 21<sup>st</sup>, as we draft our plans, all human systems will have to take into account limits, the need for reductions, and the need to move back within the safe operating boundaries for planet Earth.

58 Statistics Canada Tables 32-10-0274-01 and 32-10-0039-01; Maurice Korol and Gina Rattray, "Canadian Fertilizer Consumption, Shipments and Trade: 1999/2000" (Ottawa: Agriculture and Agri-Food Canada, 2001), [http://www5.agr.gc.ca/resources/prod/doc/pol/pub/canfert/pdf/canfert99\\_00\\_e.pdf](http://www5.agr.gc.ca/resources/prod/doc/pol/pub/canfert/pdf/canfert99_00_e.pdf); Statistics Canada and Dominion Bureau of Statistics, "The Fertilizer Trade," various years from 1926 to 1948, accessed June 29, 2022, <https://publications.gc.ca/site/eng/9.853796/publication.html>.

59 While acres have shifted to canola and corn from wheat, etc. Canadian wheat production tonnage continues to trend upward, is near a record high, and exceeds tonnage of either canola or corn. See Statistics Canada Table 32-10-0359-01.

60 Nutrien Ltd., "Nutrien Fact Book 2022" (Saskatoon: Nutrien, June 2022), 20, <https://nutrien-prod-asset.s3.us-east-2.amazonaws.com/s3fs-public/uploads/2022-06/Nutrien%202022%20Fact%20Book.pdf>.



**Figure 8. Per-capita emissions from nitrogen fertilizer use, selected countries, kilograms CO<sub>2</sub>e per capita.**

Source: Reproduced from Menegat et al.<sup>61</sup>

On the whole, North America has the highest per-capita nitrogen creation rate in the world—well above those of other regions and double the global average. Table 1 compares rates of net anthropogenic nitrogen inputs (NANI). NANI includes all human-created reactive nitrogen—fertilizer, combustion-related, and nitrogen-fixing crops—but is dominated by fertilizer. If the world must reduce fertilizer consumption to deal with a nitrogen crisis, it appears that we in North America, with the highest rates of creation and use, may need to make the first and deepest reductions. Knowing this can focus our minds: We must find ways to produce food and sustainable farm incomes that rely less on fertilizers.

	NANI (kg N/cap/yr)					Population (× 10 <sup>9</sup> )					NANI increase rate (%)	Population increase rate (%)
	1961	1980	1990	2000	2009	1961	1980	1990	2000	2009		
Asia	8	14	17	19	22	1.70	2.63	3.2	3.71	4.12	190	143
Caribbean	8	18	18	11	9	0.02	0.03	0.03	0.04	0.04	10	97
Europe	25	46	44	28	30	0.65	0.69	0.72	0.73	0.73	19	13
Latin America	18	21	19	18	29	0.20	0.34	0.41	0.49	0.55	57	172
North Africa	15	19	19	20	20	0.06	0.11	0.14	0.17	0.2	29	247
North America	52	64	59	57	57	0.21	0.25	0.28	0.31	0.34	9	63
Oceania	23	17	30	48	40	0.02	0.02	0.03	0.03	0.04	75	162
Sub Saharan Africa	20	15	13	11	10	0.22	0.37	0.49	0.64	0.82	−49	276
Globe	16	23	23	21	24	3.07	4.44	5.30	6.12	6.84	49	123

**Table 1. Regional per-capita rates of net anthropogenic nitrogen inputs (NANI).**

Source: Reproduced from Han et al., “Global and Regional Estimation of Net Anthropogenic Nitrogen Inputs (NANI).”<sup>62</sup>

Exacerbating the situation regarding nitrogen, humans have also multiplied the flows of the other main plant nutrients, doubling or tripling the flow of phosphorus (P) available to terrestrial ecosystems,<sup>63</sup>

61 Menegat, Ledo, and Tirado, “Greenhouse Gas Emissions from Global Production and Use of Nitrogen Synthetic Fertilisers in Agriculture,” Figure 1.

62 Yuguo Han et al., “Global and Regional Estimation of Net Anthropogenic Nitrogen Inputs (NANI),” *Geoderma* 361 (2020).

63 Elena Bennett et al., “Human Impact on Erodable Phosphorus and Eutrophication: A Global Perspective,” *BioScience* 51, no. 3. (2001): 229; Fred Mackenzie et al., “Century-Scale Nitrogen and Phosphorus Controls of the Carbon Cycle,” *Chemical Geology* 190 (2002): 14, 18; Gara Villalba et al., “Global Phosphorus Flows in the Industrial Economy from a Production Perspective,” *Journal of Industrial Ecology* 12, no. 4 (2008): 557–558; Vaclav Smil, “Phosphorus in the Environment: Natural Flows and Human Interferences,” *Annual Review of Energy and the Environment* 25, no. 1 (2000).



increasing the flow of potassium (K) via mined potash,<sup>64</sup> and doubling or tripling the flow of sulphur (S).<sup>65</sup> Humans have seized control of the biosphere's nutrient flows and twisted the dials higher and higher.<sup>66</sup> This is what is meant by the term "Anthropocene": a human-controlled Earth.

Through the production of nitrogen fertilizers, the increase in the area of nitrogen-fixing crops, and the combustion of fossil fuels, humans each year are now adding to the biosphere more than 191 million tonnes of new N<sub>r</sub>. Table 2 shows the tonnages of human-made and natural-source nitrogen.

**Table 2. Contributions of human-made reactive nitrogen to terrestrial systems, and the pre-industrial baseline.**

Sources of nitrogen (units: millions of tonnes per year)	1910 ("pre-industrial" or "natural" flows)	1960	circa 2015
Synthetic fertilizer	1.0	12	110
Cultivation-induced biological nitrogen fixation	0.4	12	43
Fossil fuel combustion (NO <sub>x</sub> )	2.5	15	38
<b>Total anthropogenic</b>	<b>3.9</b>	<b>39</b>	<b>191</b>
<i>Total natural terrestrial (lightning &amp; natural N-fixing plants)</i>	<i>90</i>	<i>90</i>	<i>90</i>
<b>Total</b>	<b>93.9</b>	<b>129</b>	<b>281</b>
Multiple of natural	1x	1.4x	3x

Source: Data from Battye et al. 2017.<sup>67</sup> Cross-referenced against other sources.<sup>68</sup>

The rate of N fixation determines the structure of ecosystems and, hence, the biosphere.<sup>69</sup> And though we have tripled terrestrial nitrogen flow rates globally, (i.e., averaged across the planet's land surfaces) regionally the increases are far greater. About 84 percent of nitrogen is applied in North America, Europe, and Asia.<sup>70</sup> According to biogeochemist and global expert on nitrogen flows James Galloway, in many parts of those continents, nitrogen flows are now ten times higher than the natural/pre-industrial rates.<sup>71</sup> N flows through Canadian Prairie croplands may be roughly seven times higher than the natural/pre-settlement rates.<sup>72</sup>

64 Jordi Sardans and Josep Peñuelas, "Potassium: A Neglected Nutrient in Global Change," *Global Ecology and Biogeography* 24, no. 3 (2015): Figure 1; William Schlesinger, "Some Thoughts on the Biogeochemical Cycling of Potassium in Terrestrial Ecosystems," *Biogeochemistry* 154, no. 2 (2021).

65 T.A. Rappold and K.S. Lackner, "Large Scale Disposal of Waste Sulfur: From Sulfide Fuels to Sulfate Sequestration," *Energy* 35 (2010): 1369; James Galloway, "Anthropogenic Mobilization of Sulphur and Nitrogen: Immediate and Delayed Consequences," *Annual Review of Energy and the Environment* 21 (1996): 271; James Galloway, "Acidification of the World: Natural and Anthropogenic," *Water, Air, and Soil Pollution* 30 (2001): 17, 19.

66 Darrin Qualman, *Civilization Critical: Energy, Food, Nature, and the Future* (Halifax; Winnipeg: Fernwood Publishing, 2019), Ch. 28, "Taking Control of Everything."

67 Battye, Aneja, and Schlesinger, "Is Nitrogen the next Carbon?," 898 & Table 1.

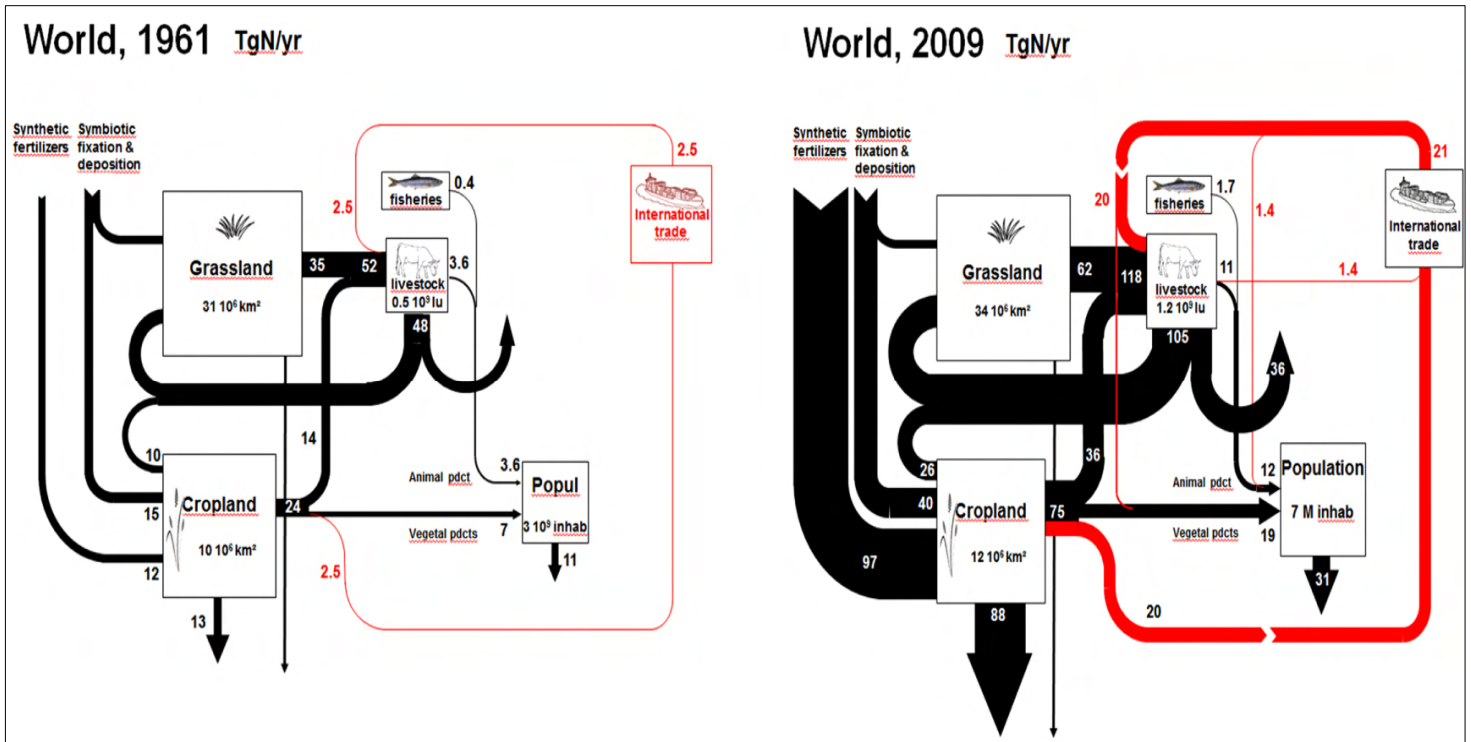
68 James Galloway and Ellis Cowling, "Reflections on 200 Years of Nitrogen, 20 Years Later," *Ambio* 50, no. 4 (2021); Battye, Aneja, and Schlesinger, "Is Nitrogen the next Carbon?"; D. Fowler et al., "Effects of Global Change During the 21st Century on the Nitrogen Cycle," *Atmos. Chem. Phys.* 15, no. 24 (2015); David Fowler et al., "The Global Nitrogen Cycle in the Twenty-First Century," *Phil. Trans. R. Soc. B* 368, no. 1621 (2013); James Galloway et al., "Nitrogen Cycles: Past, Present, and Future," *Biogeochemistry* 70, no. 2 (2004); Alan Townsend and Robert Howarth, "Fixing the Global Nitrogen Problem," *Scientific American* 302, no. 2 (2010); James Galloway et al., "Transformation of the Nitrogen Cycle: Recent Trends, Questions, and Potential Solutions," *Science* 320, no. 5878 (2008); James Galloway and Ellis Cowling, "Reactive Nitrogen and The World: 200 Years of Change," *AMBIO: A Journal of the Human Environment* 31, no. 2 (2002).

69 Townsend et al., "Human Health Effects of a Changing Global Nitrogen Cycle," 241.

70 Nutrien, "Nutrien Fact Book 2020" (Saskatoon: Nutrien, 2020), 48, <https://nutrien-prod-asset.s3.us-east-2.amazonaws.com/s3fs-public/uploads/2020-10/Nutrien%20Fact%20Book%202020.pdf>.

71 Galloway et al., "Transformation of the Nitrogen Cycle," 889–90; UNESCO & SCOPE et al., "Human Alteration of the Nitrogen Cycle: Threats, Benefits and Opportunities" (Paris: UNESCO-SCOPE, April 2007), <https://unesdoc.unesco.org/ark:/48223/pf0000150916>.

72 Taking a global average pre-industrial flow of 90 million tonnes N per year, we get a rough global average of 5 kg per hectare per year for the entire land surface of the Earth. Prairie grassland flows would probably be higher: perhaps 10 kg per hectare. Current Prairie N fertilizer rates average roughly 70 kg N per hectare per year. Actual Prairie natural/pre-settlement rates are uncertain, so future research and calculations can refine this rough 7x multiple.



**Figure 9. A representation of nitrogen flows through the global agri-food system, comparing 1961 and 2009.**

Source: Reproduced from Lassaletta et al.<sup>73</sup> Note: The units, TgN/yr, teragrams of nitrogen per year, are equal to millions of tonnes of N per year.

Figure 9 compares global agricultural nitrogen flows across a nearly 50-year span. Note the multiplication of flows into croplands, grasslands, livestock systems, and human populations. Synthetic fertilizer is the primary source of those increased flows. This graphic is a picture of humanity's alterations of one of the most important flows in Earth's biosphere; of one aspect of the Anthropocene; of one of the transgressions of "planetary boundaries." It is a schematic of the nitrogen crisis.

## The future of nitrogen fertilizer production and use

Already high, global nitrogen fertilizer application rates and overall volumes continue to rise. What are the projections for the future? James Galloway and his coauthors project that unless current trends are altered, nitrogen flows on several continents may double during the first half of the 21<sup>st</sup> century.<sup>74</sup> The United Nations Food and Agricultural Organization (UN FAO) projects that, under most scenarios, nitrogen-in-fertilizer consumption will be 50 percent higher in 2050 than in 2012.<sup>75</sup> Jose Mongollón et al. project that fertilizer use could double, or more, by 2050.<sup>76</sup> Other projections include

73 Luis Lassaletta et al., "Nitrogen Use in the Global Food System: Past Trends and Future Trajectories of Agronomic Performance, Pollution, Trade, and Dietary Demand," *Environmental Research Letters* 11, no. 9 (2016): 095007.

74 Galloway et al., "Transformation of the Nitrogen Cycle"; James Galloway et al., "Nitrogen: The Historical Progression from Ignorance to Knowledge, with a View to Future Solutions," *Soil Research* 55, no. 6 (2017).

75 United Nations Food And Agriculture Organization, "The Future of Food and Agriculture: Alternative Pathways to 2050" (Rome: UN FAO, 2018), 139, <https://www.fao.org/policy-support/tools-and-publications/resources-details/en/c/1259562/>.

76 J.M. Mongollón et al., "Assessing Future Reactive Nitrogen Inputs into Global Croplands Based on the Shared Socioeconomic Pathways," *Environmental Research Letters* 13, no. 4 (2018): 044008.

those by Fowler et al.,<sup>77</sup> Tilman et al.,<sup>78</sup> Bouwman et al.,<sup>79</sup> Vishwakarma et al.,<sup>80</sup> and others. For a list of estimates and sources, see Galloway, Bleeker, and Erisman, 2021.<sup>81</sup>

Not every scenario projects increased tonnage. Many studies that look to 2050 or beyond also include scenarios in which societies undertake ambitious measures to bend the upward-trending fertilizer-use curves downward, measures including changing diets and reducing food waste or increasing nitrogen use efficiency. Most scenarios, however, project sharply increased fertilizer use—up 50 percent, 100 percent, or more. Having pushed global nitrogen flows to three times their pre-industrial levels and far past safe operating limits, humans now seem intent on pushing flows to four- or five-times natural rates.

What might we project for Canadian nitrogen tonnage under a business-as-usual scenario? A starting point is to note that fertilizer rates and overall tonnage continue to rise sharply (see Figure 7, page 21). Moreover, our federal government is intent on increasing agri-food exports (details in Ch. 10). In practice, export maximization spurs yield and production maximization, leading to input maximization—especially fertilizer (see Figure 15, page 46). A third factor is aggressive efforts both in Canada and worldwide to wrest a range of new food, fibre, and fuel products from Earth's farmland area, including feedstocks for biofuels for cars and trucks and soon for jets and ships; biomaterial feedstocks to replace petroleum plastics; feedstocks for bioenergy electricity production (aka BECCS); and more. If we are to extract hundreds-of-millions more tonnes of agricultural materials for energy production and industrial uses, we will have to apply millions of tonnes more fertilizer. Yet this projected increase in fertilizer use and related emissions is incompatible with the pressing need to reach near-zero emissions by mid-century. Canada and its farmers seem caught. Fortunately, alternatives exist. Incremental and efficiency-based measures are explored in Chapter 13. But real solutions become possible only when we embrace limits, step off the input-use treadmill, and begin a process of transformation (see Ch. 15).

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77 Fowler et al., "Effects of Global Change During the 21st Century on the Nitrogen Cycle."

78 David Tilman et al., "Forecasting Agriculturally Driven Global Environmental Change," *Science* 292, no. 5515 (2001).

79 Lex Bouwman et al., "Exploring Global Changes in Nitrogen and Phosphorus Cycles in Agriculture Induced by Livestock Production Over the 1900–2050 Period," *Proceedings of the National Academy of Sciences* 110, no. 52 (2013).

80 Srishti Vishwakarma, Xin Zhang, and Nathaniel Mueller, "Projecting Future Nitrogen Inputs: Are We Making the Right Assumptions?," *Environmental Research Letters* 17, no. 5 (2022).

81 James N. Galloway, Albert Bleeker, and Jan Willem Erisman, "The Human Creation and Use of Reactive Nitrogen: A Global and Regional Perspective," *Annual Review of Environment and Resources* 46, no. 1 (2021): Table 1.

## 5. The Green Revolution

*It's really impossible to understand the massive growth of the human population, to understand the urbanization of our species, to understand our tremendous, increasing ecological impact on the world, unless we understand Norman Borlaug and the Green Revolution.*

—Historian Tore Olsson, PBS documentary: “The Man Who Tried to Feed the World.”<sup>82</sup>

*If the high-yielding dwarf wheat and rice varieties are the catalysts that have ignited the green revolution, then chemical fertilizer is the fuel that has powered its forward thrust. The responsiveness of the high-yielding varieties has greatly increased fertilizer consumption.*

—Norman Borlaug, father of the Green Revolution, Nobel Prize speech, 1970.<sup>83</sup>

The world’s massive dependence on nitrogen fertilizer did not occur by accident—not merely as a result of farmers putting a bit more fertilizer on each acre, each year. Rather, farmers’ dependence on fertilizer is the result of intense research, of funding by numerous governments and institutions, and of decades-long efforts to re-engineer crops to make them ready conduits for multi-megatonne flows of industrial fertilizers.

Earth’s plants and ecosystems initially resisted human efforts to push ever-larger quantities of nitrogen into fields and food supplies. Humans had to re-engineer crops and farming systems in order to enable them to absorb and convert massive quantities of fertilizers. That re-engineering of crop varieties and agriculture is what we now refer to as the Green Revolution.

As a term, “Green Revolution” carries several overlapping meanings. It refers to a period of research from the 1940s through the 1960s. It also refers to the outcomes of that research: re-engineered crops and attendant technologies that have meant a sustained period of rising grain yields beginning in the 1960s and credited with expanding global food supplies and averting famines.

There are, however, at least two camps when it comes to understanding what the Green Revolution actually was and is. Some view it as a triumph of plant breeding: human ingenuity found and interbred crop varieties that now produce higher yields. Dwarf and semi-dwarf varieties of wheat, rice, and other crops replaced traditional long-stem tall varieties. The Green Revolution produced miracle seeds—the “high-yielding varieties.” In this narrative, farsighted governments, foundations, research centres, and development agencies harnessed and funded human innovation to produce improved crop varieties and expanded yields.

There is, however, another version of this story, one in which the Green Revolution is not so much about seeds and inherent yield and human cleverness, but rather about fossil fuels and fertilizers. In this version, the Green Revolution sought to breed out traits that made plants ill-suited to high rates of fertilizer so as to pave the way for yields increasingly fuelled by synthetic nitrogen and other inputs.

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82 “American Experience: The Man Who Tried to Feed the World,” KPBS Public Media, April 20, 2020, <https://www.kpbs.org/news/arts-culture/2020/04/20/american-experience-man-who-tried-feed-world>; *The Man Who Tried To Feed the World: Chapter 1 | American Experience | PBS* (PBS), accessed June 20, 2022, <https://www.pbs.org/wgbh/americanexperience/features/man-who-tried-to-feed-the-world-chapter-1/>.

83 “The Nobel Peace Prize 1970: Norman Borlaug,” NobelPrize.org, n.d., <https://www.nobelprize.org/prizes/peace/1970/borlaug/facts/>.

Crop varieties that had existed for millennia in nutrient-scarce environments performed poorly in nutrient-enriched fields. The Green Revolution fixed that problem. Writer and historian Reay Tannahill explains:

One of the great barriers to increased grain production in hot countries is that when traditional plants are heavily fertilized, they shoot up to an unnatural height and then collapse.... During the Mexican experiments [in the 1950s and '60s], however, and after tests involving 40,000 crossbreeds of plant[s], it was found that if a short stemmed grain [was] thickly sown at the right depth and adequately irrigated, it could take massive doses of fertilizer without becoming lanky and give spectacularly high yields.<sup>84</sup>

The US National Academy of Sciences similarly explains that “Borlaug recognized the potential value of shorter (“semi-dwarf”) wheats possessing stronger stems, which could respond to increased water and fertilizer treatments by producing more grain but would not fall over (called lodging) with a heavy head of grain.”<sup>85</sup>

Those who point to fertilizer as key to the Green Revolution emphasize that the short-stemmed new varieties were not inherently higher-yielding (they might not significantly outyield their tall-stemmed predecessors in an unfertilized situation). Rather, Green Revolution varieties had been selected and tailored for the process of turning fertilizers, pesticides, irrigation water, and other inputs into larger yields. While this may seem a subversive characterization, remember that none other than Norman Borlaug, in accepting his Nobel Prize, called chemical fertilizer “the fuel” for the Green Revolution.

Table 3, below, comes from a journal article entitled “Crop Intensification, Land Use, and on-Farm Energy-Use Efficiency During the Worldwide Spread of the Green Revolution.”<sup>86</sup> The values in the table compare the tonnages of various farm inputs in 1961 (the eve of the spread of Green Revolution varieties) to recent times. Note the ninefold increase in consumption of nitrogen-in-fertilizer—the increase in “fuel.”

**Table 3. Agricultural input use and multiples comparing pre- and post-Green-Revolution periods.**

	N fertilizer, Mt		P fertilizer, Mt		K fertilizer, Mt		Machinery, Mt		Fuel, Mt		Cultivated land, Mha		Irrigated land, Mha	
	1961	2014	1961	2014	1961	2014	1961	2014	1961	2014	1961	2014	1961	2014
Continent														
Africa	0.07	1.08	0.15	0.52	0.04	0.29	1.02	1.3	0.51	0.65	76	120	2	5
Asia	0.34	9.23	0.24	3.28	0.04	3.84	0.85	35.45	0.32	13.29	115	161	15	40
MIC	2.56	55.77	1.34	24.82	0.85	17.17	3.1	75.64	1.55	37.82	341	361	94	178
Europe	4.37	12.63	4.65	2.83	4.49	2.91	40.2	59.74	17.59	26.14	353	288	14	13
Latin America	0.28	7.32	0.27	6.42	0.14	6.26	2.85	14.71	1.25	6.43	83	175	5	18
North America	3.16	15.26	2.73	5.15	2.17	4.97	96.31	87.31	32.1	29.1	235	208	20	27
Oceania	0.04	1.4	0.59	0.91	0.05	0.23	4.93	5.24	1.64	1.75	30	47	1	3
Total	11	103	10	44	8	36	149	279	55	115	1,234	1,361	151	284
Rate of increase		x9		x4		x5		x2		x2		x1.1		x1.9

Source: Reproduced from Pellegrini and Fernandez, 2018.<sup>87</sup>

This story has yet another aspect: Green Revolution seeds are part of a *package* that includes, not just fertilizers, but also insecticides, herbicides, fungicides, and, often, irrigation water. In nature, plants

84 Reay Tannahill, *Food in History* (New York: Three Rivers Press, 1988), 336.

85 Ronald Phillips and National Academy of Sciences, “Norman E. Borlaug: 1914–2009,” Biographical Memoirs (National Academy of Sciences, 2009), <http://www.nasonline.org/publications/biographical-memoirs/memoir-pdfs/borlaug-norman.pdf>.

86 Pedro Pellegrini and Roberto Fernández, “Crop Intensification, Land Use, and On-Farm Energy-Use Efficiency During the Worldwide Spread of the Green Revolution,” *Proceedings of the National Academy of Sciences* 115, no. 10 (2018).

87 Pellegrini and Fernández, “Crop Intensification, Land Use, and on-Farm Energy-Use Efficiency During the Worldwide Spread of the Green Revolution,” Table 1.

often evolve to be tall in order to out-compete weeds. Breeding plants to be shorter, as was done by Borlaug and his colleagues, makes those plants more dependant on chemicals to control weeds and other competitors. Another effect of the Green Revolution was to homogenize the global seed supply—to reduce the tremendous diversity of seeds and production practices and local knowledge built up over countless generations. By eradicating<sup>88</sup> alternative seeds and systems, the Green Revolution package of seeds, fertilizers, and pesticides installed itself as a fait accompli.

It took decades of research and innovation and a concerted, sustained push by governments around the world to get us to a place where farmers are massively dependent on chemical fertilizers and other inputs. It will take efforts on a similar scale to get us to a new place where we are much less dependent. And because of climate change and other environmental impacts, we must proceed rapidly.

A transition to a new, less-fertilizer-dependent, lower-emission future cannot be solely the responsibility of farmers. It will not come merely as the result of “efficiency” or market forces or a simplistic focus on adoption of “best management practices.” Rather, governments, universities, and other institutions must provide significant resources and sustained leadership as our global civilization of eight billion souls makes this critical transition.

A Nobel Prize was awarded to the person who figured out how to push tens-of-millions of tonnes of fertilizer into global food systems. The Prize for the person who figures out how to slash those nitrogen flows has yet to be awarded. And, just as in the Green Revolution, accomplishing this goal will take intense, sustained, and concerted efforts by governments, researchers, and others.

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88 “Eradicated” is used advisedly, because it derives from “radix” or “root” and means “to pull out by the root.”

*CO<sub>2</sub>* = carbon dioxide | *CO<sub>2</sub>e* = carbon dioxide equivalent | *N<sub>2</sub>O* = nitrous oxide | *CH<sub>4</sub>* = methane | *NH<sub>3</sub>* = ammonia | *NO<sub>x</sub>* = nitrogen oxides | *Mt* = million tonnes



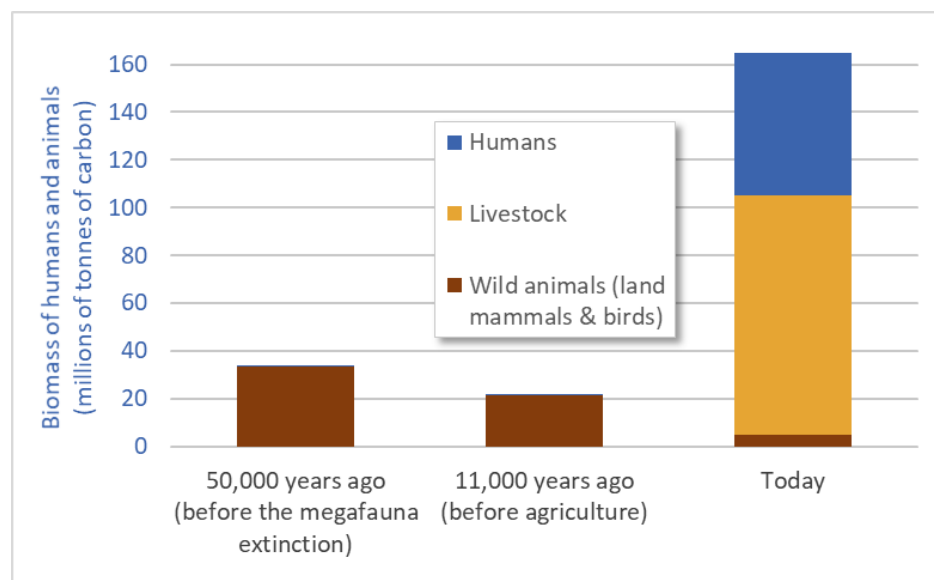
## 6. The Livestock Revolution

*The 20<sup>th</sup> century “green revolution” has depended critically on ... additional nutrient sources, while becoming the basis for an ongoing “livestock revolution,” where relatively cheap grain and other produce ... are allowing intensification of livestock farming, greatly increasing per-capita meat and dairy production. ... The global nitrogen cycle is ... dominated by humanity’s use of N<sub>r</sub> to raise livestock.*

—Mark Sutton et al., *Our Nutrient World*.<sup>89</sup>

Huge portions of our fertilizer-expanded grain harvests go, not to feeding people, but to feeding livestock. We are turning fossil fuels into nitrogen fertilizers into expanded harvests of feedgrains into unprecedented numbers of domesticated food animals. ...*wholly* unprecedented.

Figure 10 shows the mass of humans, of our domesticated livestock, and of terrestrial wild animals (mammals and birds). Three periods are shown. The first, on the left, is 50,000 years ago: before the Quaternary megafauna extinction when *Homo sapiens* entered Eurasia and contributed to the extinction of about half the planet’s large animal species. In the middle of the graph is the period around 11,000 years ago—before humans began practicing agriculture. On both the left-hand side and the centre, the mass of humans is so small as to not be visible on the graph. On the right is the situation today: Humans and our domesticated livestock now dominate the Earth.



**Figure 10. Mass of humans, livestock, and terrestrial wild animals.**

Sources: Bar-On, Phillips, and Milo; Barnosky; and Smil.<sup>90</sup>

<sup>89</sup> Mark Sutton et al., *Our Nutrient World: The Challenge to Produce More Food and Energy with Less Pollution* (Edinburgh: NERC/Centre for Ecology & Hydrology, 2013), viii and 21.

<sup>90</sup> Yinon Bar-On, Rob Phillips, and Ron Milo, “The Biomass Distribution on Earth,” *Proceedings of the National Academy of Sciences* 115 (2018); Anthony Barnosky, “Megafauna Biomass Tradeoff as a Driver of Quaternary and Future Extinctions,” *Proceedings of the National Academy of Sciences* 105 (2008); Vaclav Smil, *Harvesting the Biosphere: What We Have Taken from Nature* (Cambridge, MA: MIT Press, 2013). The picture painted by Bar-On et al. and depicted in the graph is so surprising as to raise doubts. But their analysis in 2018 came to the same conclusions as Smil’s in 2013. In preparing this report, the NFU contacted Bar-On and Milo to ask if there has been objections or revisions in the four years since their article was published. Their answer was “no”; that their analysis has met with general acceptance.

The mass of livestock animals on Earth today is three or four times the mass of wild animals in previous eras—the number of animals today is *unnaturally* large. Current numbers include about 1.5 billion cattle; 3.3 billion sheep, goats, and hogs; and tens-of-billions of chickens, turkeys, and ducks.<sup>91</sup>

The mass of livestock animals today dwarfs the mass of wild animals in past eras, but even more so, it dwarfs the mass of wild animals *today*. Our livestock outweighs remaining wild animals 20-to-1. (One stark specific: The weight of the world's chickens is about twice the weight of all the remaining wild birds combined.<sup>92</sup>) Add the biomass of humans to that of livestock, and we find that we and our pigs, chickens, etc. outweigh remaining wild animals 32-to-1, with wild animals making up just 3 percent of terrestrial animal biomass. This is the main reason why the Earth is undergoing the most rapid extinction event in 65 million years.<sup>93</sup> Threatening to exacerbate this dire situation, global meat production, having doubled since 1986,<sup>94</sup> is on track to double again this century.<sup>95</sup>

How did we achieve this huge increase in animal numbers and mass? Fertilizers. Though fertilizer company executives and other advocates of the status quo feign concern for “feeding the world,” a large and growing portion of our fertilizer megatonnage goes to produce livestock feedgrains, liquid biofuels, industrial feedstocks, food that is wasted, hyper-processed and nutritionally disfigured foods, cotton and other fibres for “fast fashion,” and, in the future, perhaps solid-fuel biomass feedstocks to replace fossil fuels in electricity generation to power ever-rising living standards.<sup>96</sup> When it comes to the output tonnage and range of products we demand from our farmland area, there are no limits.

We need to be clear about what we are actually doing with our fertilizers and crops. As Sutton et al. note, “The global nitrogen cycle is ... dominated by humanity's use of N<sub>r</sub> to raise livestock”<sup>97</sup> [italics added]. Much more than half our fertilizer use and crop production are devoted to livestock production (see Figure 12, page 32). Feeding grain to livestock is inefficient. Doing so converts a large number of Calories into a much smaller number, and similarly converts several units of nitrogen-rich protein into a few. In general, 5 to 10 grain Calories or units of protein are required to make one meat Calorie or unit of protein,<sup>98</sup> with poultry being the most efficient converters of grain, and beef cattle the least.

Most North American cattle are fed and finished on a mix of grass, forage, and grain. The preceding feed conversion ratios take that into account (see Figure 11, below). Cattle can be fed and finished wholly on unfertilized grass and forages—on a number of farms that is exactly what happens—and those are very positive production systems with many environmental benefits including maintaining biodiverse grassland ecosystems. Without grain feeding, however, global cattle numbers would be much lower. Likewise, a smaller number of hogs and chickens could be fed on otherwise-wasted food and other by-products but, again, livestock numbers would have to be much smaller than those of today.

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91 United Nations Food and Agriculture Organization (UN FAO), FAOSTAT website, “Production: Live animals.”

92 Yinon Bar-On, Rob Phillips, and Ron Milo, “The Biomass Distribution on Earth,” *Proceedings of the National Academy of Sciences* 115, no. 25 (2018): 3.

93 *Millennium Ecosystem Assessment, Ecosystems and Human Well-being: Synthesis, 2005*, (Island Press, Washington), 5, 36, & 38.

94 FAOSTAT website, “Production: Livestock primary,”

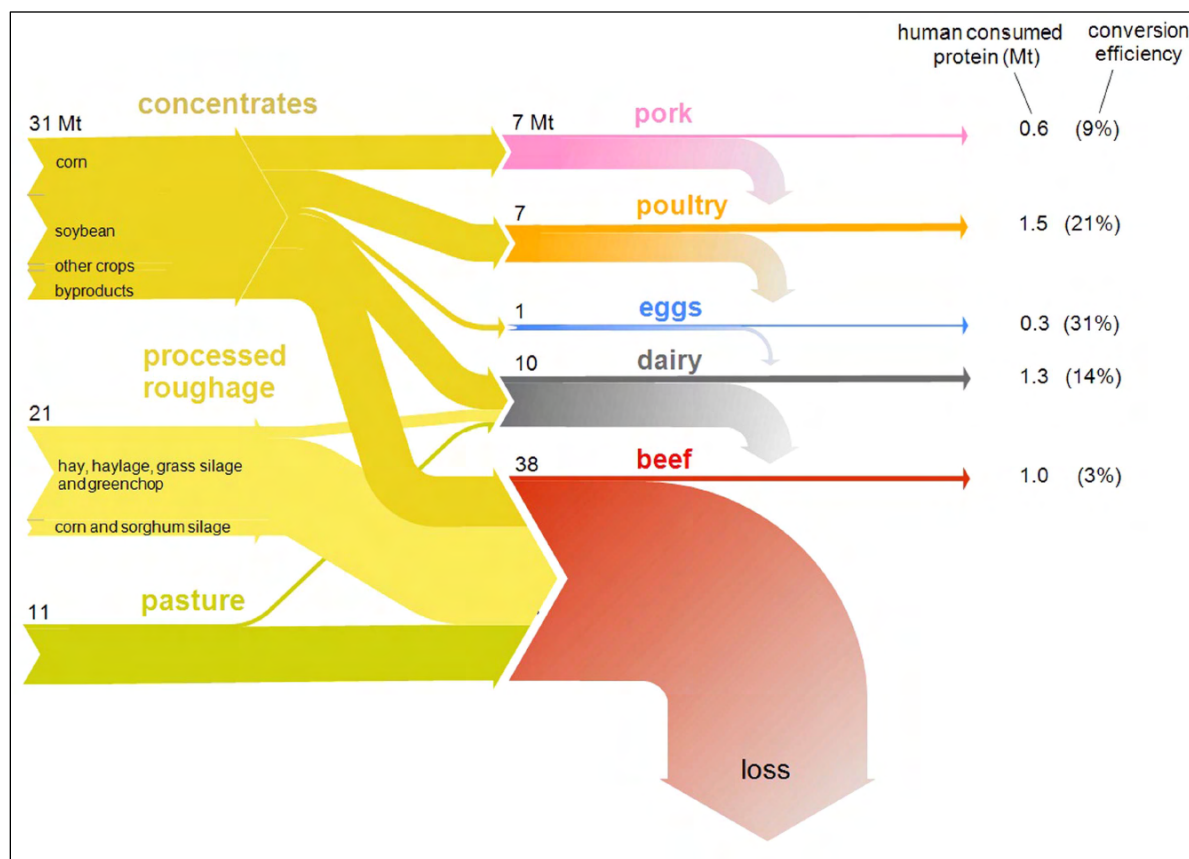
95 Nikos Alexandratos, Jelle Bruinsma, and others, “World Agriculture Towards 2030/2050: The 2012 Revision,” EAS Working Paper (Rome: UN FAO, 2012); Nathan Pelletier and Peter Tyedmers, “Forecasting Potential Global Environmental Costs of Livestock Production 2000–2050,” *Proceedings of the National Academy of Sciences* 107, no. 43 (2010).

96 Deepak Ray et al., “Crop Harvests for Direct Food Use Insufficient to Meet the UN's Food Security Goal,” *Nature Food* 3, no. 5 (2022).

97 Sutton et al., *Our Nutrient World*, viii and 21.

98 Alon Shepon et al., “Energy and Protein Feed-to-Food Conversion Efficiencies in the US and Potential Food Security Gains from Dietary Changes,” *Environmental Research Letters* 11 (2016); Vaclav Smil, “Nitrogen and Food Production: Proteins for Human Diets,” *AMBIO: A Journal of the Human Environment* 31, no. 2 (March 2002): Figure 5.

Figure 11, below, shows the protein inputs into US livestock production and the protein outputs. It also includes the ratio percentages of protein-out to protein-in. Protein is about 16 percent nitrogen by weight, so the percentages can also be thought of as the percentage of nitrogen-out relative to the quantity of nitrogen-in. For example, for every 100 units of N in corn and other grains and oilseeds fed to hogs, about 9 units of N emerge in edible protein. When we take into account the fact that about half the N we apply to fields misses the crop altogether, we find that farmers need to apply 200 units of fertilizer N to get 100 units of crop N to get 9 units of edible N in pork. Overall, globally, 6 to 7 percent of the  $N_r$  consumed by livestock reaches the human food supply.<sup>99</sup> Canadian numbers would be comparable.



**Figure 11. Protein inputs and outputs and conversion efficiency percentages for US livestock production systems.**

Source: Reproduced from Shepon et al., 2016.<sup>100</sup>

In effect, we are producing huge quantities of N in Haber-Bosch nitrogen factories, then funnelling much of that N into meat production systems that cause most of that N to be lost. Stated in the converse: It is only because we can produce huge quantities of synthetic nitrogen and plant protein and calories that we can have these huge numbers of relatively inefficient grain-consuming livestock. Hydrocarbons fuel Haber-Bosch nitrogen fertilizer factories; nitrogen fertilizer fuels the Green Revolution; and the Green Revolution fuels the Livestock Revolution. Yield maximization via fertilizer is half the story; but dissipation, inefficiencies, and system losses—via biofuels, livestock feedgrains, food waste, over-processing, etc.—is the other half. As we reduce output wastage we can also reduce input tonnage.

99 Sutton et al., *Our Nutrient World*, 21; Shepon et al., “Energy and Protein Feed-to-Food Conversion Efficiencies in the US and Potential Food Security Gains from Dietary Changes,” Figure 2.

100 Shepon et al., “Energy and Protein Feed-to-Food Conversion Efficiencies in the US and Potential Food Security Gains from Dietary Changes,” Figure 2.

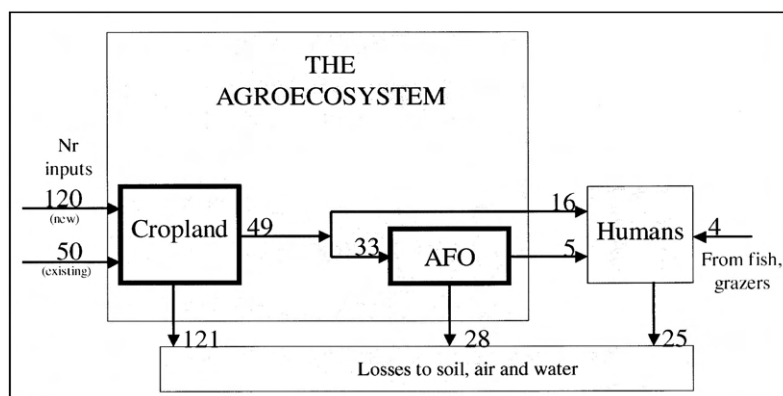
## 7. Most nitrogen fails to reach our crops and food

*Less than half of the fixed nitrogen added by agriculture ends up in our harvested crops....*  
—Robert Socolow, “Nitrogen Management and the Future of Food.”<sup>101</sup>

*Most of the reactive nitrogen we make ... does not end up in the food we eat. Rather it migrates into the atmosphere, rivers and oceans, where it makes a Jekyll and Hyde style transformation from do-gooder to rampant polluter.*  
—Alan Townsend and Robert Howarth, “Fixing the Global Nitrogen Problem.”<sup>102</sup>

Farmers and policymakers tend to think of nitrogen fertilizer as contributing to higher crop yields: more kgs of N → more kgs of grain. But incorporation into harvested crops is just one path for the nitrogen we apply to soils. Indeed, *half* of the nitrogen we apply as fertilizer *misses* our intended targets and takes other routes through the biosphere: through water, the atmosphere, and natural ecosystems.<sup>103</sup>

Figure 12 shows global flows of reactive nitrogen through crop and animal production systems. It shows that humans add to agricultural systems about 120 million tonnes (Mt) annually of new reactive nitrogen (in the forms of fertilizer and cultivation-induced biological nitrogen fixation in crops such as soybeans) and about 50 Mt of previously created reactive nitrogen (including crop residues and manures). Our cropland systems turn that 170 Mt of N input into 49 Mt of N output (mostly in crop protein). Of that 49 Mt, 16 is consumed directly by humans and twice that amount, 33 Mt, is fed to livestock in “animal feeding operations” (AFOs). Most of the initial 170 Mt N is lost to the atmosphere (as NO<sub>x</sub>, NH<sub>3</sub>, N<sub>2</sub>O, and N<sub>2</sub>) or to waters (as NO<sub>3</sub><sup>-</sup>), with a portion (50 Mt) recycled back to crops. Galloway et al. note: “Generally, the more N<sub>r</sub> that is added to crop agroecosystems, the more is lost through air and water pathways.”<sup>104</sup>



**Figure 12. Global nitrogen flows through crop and animal production systems, millions of tonnes of N annually.**  
Source: Reproduced from Galloway et al.<sup>105</sup>

Since only about half of our nitrogen-in-fertilizer finds its way into crops and even less finds its way into the food we eat, a critical question is: What happens to the rest of that nitrogen?

<sup>101</sup> Socolow, “Nitrogen Management and the Future of Food,” 6005.

<sup>102</sup> Townsend and Howarth, “Fixing the Global Nitrogen Problem,” 64.

<sup>103</sup> Alexander Bouwman, G. Brecht, and Klaas Van der Hoek, “Global and Regional Surface Nitrogen Balances in Intensive Agricultural Production Systems for the Period 1970-2030,” *Pedosphere* 15 (2005); Benjamin Houlton et al., “Intentional versus Unintentional Nitrogen Use in the United States: Trends, Efficiency and Implications,” *Biogeochemistry* 114, no. 1 (2013): 17 & 19; Karimi et al., “An Updated Nitrogen Budget for Canadian Agroecosystems”; Xin Zhang et al., “Quantification of Global and National Nitrogen Budgets for Crop Production,” *Nature Food* 2, no. 7 (2021).

<sup>104</sup> Galloway et al., “The Nitrogen Cascade,” 345.

<sup>105</sup> Galloway et al., “The Nitrogen Cascade,” 345.

## 8. The many other effects of N: The nitrogen cascade

*Referred to as the nitrogen cascade..., one atom of nitrogen can, in sequence, increase atmospheric O<sub>3</sub> (human health impact), increase fine particulate matter (visibility impact), alter forest productivity, acidify surface waters (biodiversity loss), ... promote coastal eutrophication, and increase greenhouse potential of the atmosphere (via N<sub>2</sub>O production).*  
—James Galloway, “Nitrogen cycles: past, present, and future.”<sup>106</sup>

*Excess fixed nitrogen, in various guises, augments the greenhouse effect, diminishes stratospheric ozone, promotes smog, contaminates drinking water, acidifies rain, eutrophies bays and estuaries, and stresses ecosystems.*  
—Robert Socolow, “Nitrogen Management and the Future of Food.”<sup>107</sup>

*Nitrogen losses to air and water play a key role in adverse impacts on human health and ecosystem functioning. Emissions of NH<sub>3</sub> and NO<sub>x</sub> affect ozone and [particulate matter] production in the atmosphere, affecting human health and terrestrial biodiversity, while nitrogen losses to groundwater and surface water affect drinking water quality and the biodiversity of aquatic ecosystems.*  
—Wim de Vries, “Impacts of Nitrogen Emissions on Ecosystems and Human Health....”<sup>108</sup>

The term “nitrogen cascade” refers to two related phenomena. First, excess reactive nitrogen in the environment creates a broad range of ecosystem and human-health impacts: acidification of soil, depletion of stratospheric ozone, algal blooms in lakes, etc. Second, and this is the reason for the word “cascade,” one single atom of reactive nitrogen can move through the system and cause several of these negative effects *in succession*. The developer of the concept, James Galloway, gives an example of the nitrogen cascade by following a single atom of nitrogen (initially in NO<sub>x</sub>) that:

can first increase [low-altitude] ozone concentrations, then decrease atmospheric visibility and increase concentrations of small particles, and finally increase precipitation acidity. Following deposition to the terrestrial ecosystem, the same N atom can increase soil acidity..., decrease biodiversity, and either increase or decrease ecosystem productivity. If discharged to the aquatic ecosystem, the N atom can increase surface water acidity and lead to coastal eutrophication. If the N atom is converted to N<sub>2</sub>O and emitted back into the atmosphere, it can first increase greenhouse warming potential and then decrease stratospheric ozone.<sup>109</sup>

The following sections deal briefly with each of these effects of reactive nitrogen, beginning in the terrestrial realm, moving to the aquatic, and concluding with the atmospheric. The sections summarize both human health and environmental impacts. Note: These impacts are complex, interactive, and not easily summarized. It is beyond the scope of this report to give comprehensive assessments. Those seeking additional clarification are encouraged to access the articles referenced and other expert sources. Our aim here is simply to demonstrate that the negative impacts from nitrogen fertilizer overuse are numerous, diverse, and serious.

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<sup>106</sup> Galloway et al., “Nitrogen Cycles,” 157.

<sup>107</sup> Socolow, “Nitrogen Management and the Future of Food,” 6001.

<sup>108</sup> Wim de Vries, “Impacts of Nitrogen Emissions on Ecosystems and Human Health: A Mini Review,” *Current Opinion in Environmental Science & Health* 21 (2021): 5.

<sup>109</sup> Galloway et al., “The Nitrogen Cascade.”

## Terrestrial: Reductions in biodiversity

Every ecosystem hosts a mix of organisms adapted to factors such as temperature, precipitation, and nutrient availability. Changes in nutrient levels, such as the chronic addition of nitrogen, will drive changes in species mixes—usually losses and ecosystem simplification or even extinctions. In a 2013 article, Erisman et al. explain that “limited amounts of natural nitrogen fixation have led to the world’s ecosystems becoming adapted to low rates of N<sub>r</sub> supply, with limited productivity but high biodiversity,” adding that “broader ecosystem-scale changes to soil and vegetation often arise from chronically elevated regional N<sub>r</sub> deposition” and that “over time, species composition changes, and diversity often declines, as characteristic species of [low-nutrient] ... habitats are out-competed by more nitrophilic or acid-resistant plants.”<sup>110</sup>

In his review article, de Vries notes that diversity losses from increased N inputs have two interrelated drivers: N enrichment and acidification.<sup>111</sup> In another review, Sala et al. note that for terrestrial ecosystems, nitrogen impacts are the third most important cause of biodiversity loss (land-use change and climate change are first and second, respectively).<sup>112</sup> Estimates indicate that 5 to 15 percent of biodiversity loss is driven by elevated N levels.<sup>113</sup> (That percentage may seem inconsequential until one remembers that current rates of extinction are now between 50 and 500 times higher than long-term normal background levels.<sup>114</sup> Biodiversity loss is not the same as extinction, but the two phenomena are related and both trends are moving in the same directions. See also Figure 10, page 29.)

## Terrestrial/water: Groundwater contamination

When nitrogen is added to soils, a portion, usually in the form of nitrate (NO<sub>3</sub><sup>-</sup>), dissolves and is washed downward into groundwater. How much of the N might end up in groundwater? A study conducted over a three-decade period in France found that “8–12% of the applied fertilizer had leaked toward the hydrosphere” and that trends suggest that, overall, “between 12 and 17% of the initially applied <sup>15</sup>N-labelled fertilizer are subject to low-dose continuous release with seepage water nitrate toward the hydrosphere [i.e., leaching] over a time period of more than eight decades.”<sup>115</sup> According to Canada’s National Inventory Report (NIR) of GHG emissions, leaching rates in this country may range from 5 to 30 percent of initial N, with the lower number applicable to drier Prairie regions.<sup>116</sup> This means that hundreds of thousands of tonnes of N enter aquifers each year.

Nitrate contamination of groundwater can create a range of human-health impacts, potentially causing or contributing to reproductive problems, methemoglobinemia (usually in infants), thyroid disease, and various cancers including colorectal, bladder, stomach, liver, breast, and ovarian and non-Hodgkin’s lymphoma.<sup>117</sup> In addition to these effects, emerging evidence points to additional health

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110 Erisman et al., “Consequences of Human Modification of the Global Nitrogen Cycle,” 2013, 1 & 4.

111 de Vries, “Impacts of Nitrogen Emissions on Ecosystems and Human Health,” 3.

112 Osvaldo Sala et al., “Global Biodiversity Scenarios for the Year 2100,” *Science* 287, no. 5459 (2000): 1770.

113 Erisman et al., “Consequences of Human Modification of the Global Nitrogen Cycle,” 2013, 7.

114 Millennium Ecosystem Assessment, *Ecosystems and Human Well-Being*, 5, 36, 38.

115 Sebilio et al., “Long-Term Fate of Nitrate Fertilizer in Agricultural Soils,” 4.

116 “National Inventory Report 1990–2020: Greenhouse Gas Sources and Sinks in Canada,” Part 1, Canada’s Submission to the United Nations Framework Convention on Climate Change (UNFCCC) (Ottawa: ECCC, April 2022), 166.

117 de Vries, “Impacts of Nitrogen Emissions on Ecosystems and Human Health,” 5; J.R. Follett and R.F. Follett, “Chapter 4 - Relationship of Environmental Nitrogen Metabolism to Human Health,” in *Nitrogen in the Environment*, ed. J.L. Hatfield and R.F. Follett (San Diego: Academic Press, 2008); Townsend et al., “Human Health Effects of a Changing Global Nitrogen Cycle”; Amir Wolfe and Jonathan Patz, “Reactive Nitrogen and Human Health: Acute and Long-Term Implications,” *Ambio* 31, no. 2 (2002); Mary Ward et al., “Drinking Water Nitrate and Human Health: An Updated Review,” *International Journal of Environmental Research and Public Health* 15, no. 7 (2018): 1557.

impacts including elevated risks for Alzheimer's disease and diabetes.<sup>118</sup> (Again, a reminder that this report is not authored by doctors or medical scientists, so those seeking details on links between groundwater nitrate and various diseases should consult cited studies and other expert sources.)

## Terrestrial/water: Soil acidification, freshwater acidification, and acid rain

Increased acidity creates a range of negative ecosystem impacts. In forests, for example, de Vries notes that "N deposition may first enhance growth and productivity through enhanced N availability, but in a later stage, it may cause eutrophication and acidification, negatively affecting nutrient balances and leading to an increased susceptibility to drought, diseases and pests" and the release of aluminum which has toxic effects on plant roots.<sup>119</sup>

Similarly, acidification can damage lakes and wetlands. "Acid rain" impacts on lakes can be dramatic, as was seen in the 1970s and '80s in North America and Europe, largely as a result of sulphur from coal-fired power plants with a secondary contribution from nitrogen oxides. Acidification of surrounding soils can also release aluminum into lakes. This combination of acidity and high aluminum concentrations is toxic to fish.<sup>120</sup> As regulations in North America and the EU have significantly reduced sulphur emissions, nitrogen has come to play a larger role in acidification in many regions.<sup>121</sup> In a journal article entitled "Acidification of the World," James Galloway explains that:

The production of  $\text{NH}_3$  by the Haber-Bosch process accounts for a substantial portion of nitrogen taken up by commercial crops.... However, about 90% of the  $\text{NH}_3$  produced is lost, prior to human consumption, much of it to the atmosphere.... When deposited in terrestrial ecosystems, the  $\text{NH}_x$  [i.e.,  $\text{NH}_3$  and  $\text{NH}_4$ , ammonium] can be nitrified, generating nitric acid.... For comparison purposes, the amount of  $\text{NH}_3$  emitted to the atmosphere from croplands and animal waste is on the order of 50 [Mt per year] globally, compared to 26 [Mt] N emitted to the atmosphere as NO from fossil fuel production.... Thus, based on atmospheric emissions alone, food production-related emissions of  $\text{NH}_3$  have twice the acidification potential as energy-related emissions of NO.<sup>122</sup>

In coming years, as fossil fuel combustion decreases and use of nitrogen fertilizer increases (as is projected), the relative contribution of fertilizer to acidification will also increase.<sup>123</sup>

## Water: Eutrophication of lakes and rivers

"Eutrophication" means nutrient enrichment, usually by nitrogen or phosphorus. Lakes and rivers often are nutrient-scarce ("oligotrophic"); hence their clear waters. Adding phosphorus and/or nitrogen can have a wide range of effects, including:

- Rapid algal growth, including harmful varieties that can release odours and toxins;

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118 Townsend and Howarth, "Fixing the Global Nitrogen Problem."

119 de Vries, "Impacts of Nitrogen Emissions on Ecosystems and Human Health," 3.

120 de Vries, "Impacts of Nitrogen Emissions on Ecosystems and Human Health," 4; Charles Driscoll et al., "Nitrogen Pollution in the Northeastern United States: Sources, Effects, and Management Options," *BioScience* 53, no. 4 (2003): 363.

121 Jan Willem Erisman et al., "Consequences of Human Modification of the Global Nitrogen Cycle," *Philosophical Transactions of the Royal Society B: Biological Sciences* 368, no. 1621 (July 5, 2013): 4, <https://doi.org/10.1098/rstb.2013.0116>.

122 James Galloway, "Acidification of the World: Natural and Anthropogenic," *Water, Air, and Soil Pollution* 130, no. 1 (2001): 18.

123 Karen Rice and Janet Herman, "Acidification of Earth: An Assessment across Mechanisms and Scales," *Applied Geochemistry* 27, no. 1 (2012).

- Loss of subaquatic plants (related to light restriction caused by increases in algae and surface plants);
- Change in the mix of fish and other animal species; and
- Reduction in oxygen levels leading to fish kills and other major impacts<sup>124</sup> (see also next section).

The addition of nitrogen or phosphorus to freshwaters can turn clear, balanced, diverse ecosystems into green, swampy, algae-dominated systems low in oxygen and with high fish and plant mortality.

## Water: Ocean “dead zones,” hypoxia, and anoxia

When nutrient levels in oceans are increased, populations of algae and other organisms also increase, even spike. Eventually, much of the biomass in these algae “blooms” dies and sinks. Decomposition requires oxygen, so levels in the water are therefore reduced. Water becomes low in oxygen (hypoxic) or very low (anoxic). Since fish and other sea life need oxygen and must work very hard to extract it from water, most sea life dies or leaves the area, creating ocean “dead zones.”

The best-known dead zone is in the Gulf of Mexico, which has sometimes grown as large as 22,000 square kms.<sup>125</sup> Located at the mouth of the Mississippi River, it is caused by nitrogen and phosphorus run-off in that watershed. But that is only one of hundreds of dead zones, and their number is increasing rapidly.<sup>126</sup> Diaz et al. write that: “Since the 1960s, the global number of hypoxic systems has about doubled every ten years up to 2000.” They project that the number and area of ocean dead zones is likely to increase: “On a global basis, by 2050, coastal marine systems are expected to experience at least a doubling in both nitrogen and phosphorus loading compared to current levels, with serious consequences to ecosystem structure and function....”<sup>127</sup> In another publication, Robert Diaz and Rutger Rosenberg underscore the fact that the number and extent of dead zones is a function of fertilizer use, stating that “the observed declines in [dissolved oxygen] have lagged about 10 years behind the increased use of industrially produced nitrogen fertilizer that began in the 1940s, with explosive growth in the 1960s to 1970s.”<sup>128</sup>

Figure 13, below, shows locations of many of the hypoxic regions around the world, including some in Canada. The red dots around the US are numerous. Sutton et al. note that “two-thirds of US coastal systems are moderately to severely impaired due to nutrient loading; there are now nearly 300 hypoxic (low oxygen) zones along the US coastline and the number is growing.”<sup>129</sup> The EU situation appears similar.

124 Gilles Pinay et al., “Eutrophication: Manifestations, Causes, Consequences and Predictability, Joint Scientific Appraisal” (France: CNRS, Ifremer, INRA, Irstea, 2017); Val Smith and David Schindler, “Eutrophication Science: Where Do We Go From Here?” *Trends in Ecology & Evolution* 24, no. 4 (2009).

125 United States Environmental Protection Agency, “Northern Gulf of Mexico Hypoxic Zone,” 2022, <https://www.epa.gov/ms-htf/northern-gulf-mexico-hypoxic-zone>.

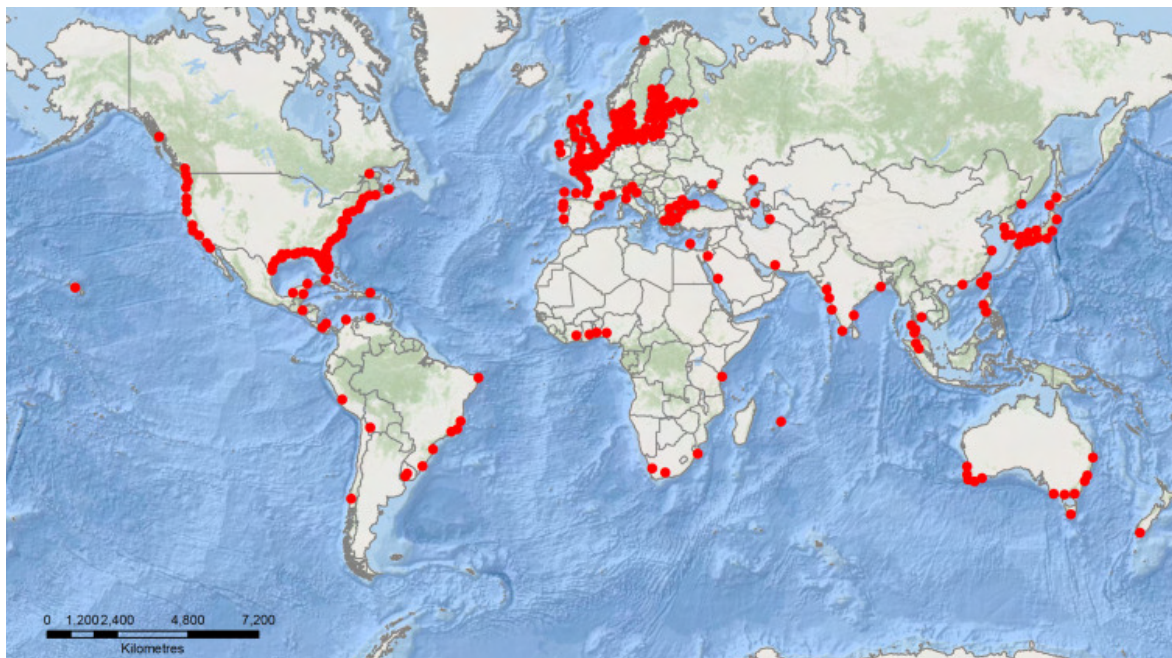
126 Robert Diaz, Rutger Rosenberg, and Kersey Sturdivant, “Hypoxia in Estuaries and Semi-Enclosed Seas,” in *Ocean Deoxygenation: Everyone’s Problem*, ed. D. Laffoley and J.M. Baxter (Gland, Switzerland: IUCN, 2019), 20.

127 Diaz, Rosenberg, and Sturdivant, “Hypoxia in Estuaries and Semi-Enclosed Seas.”

128 Robert Diaz and Rutger Rosenberg, “Spreading Dead Zones and Consequences for Marine Ecosystems,” *Science* 321, no. 5891 (2008): 926.

129 Sutton et al., *Our Nutrient World*, 83.





**Figure 13. Global map of hypoxic coastal ecosystems (aka dead zones).**

Sources: Reproduced from Altieri and Diaz.<sup>130</sup> Note: The size of the dots does not reflect the size of the zones.

In addition to dead zones, Galloway notes other effects of increasing  $N_r$  in coastal regions, including loss of seagrass beds, changes in coral reefs, increased duration of harmful algal blooms, decreased fish production, alterations in food webs, and a general loss of ecosystem diversity.<sup>131</sup>

## Atmosphere: Stratospheric ozone depletion

When located near the Earth's surface, ozone ( $O_3$ ) is a pollutant; up high, it is a sunscreen. Paradoxically, nitrogen fertilizer gives us more ozone where we do not want it (near the surface) while destroying ozone where we need it (in the stratosphere).

Applying nitrogen fertilizer releases nitrous oxide. That  $N_2O$  is primarily destroyed in the stratosphere where UV light breaks its bonds. One resulting molecule is nitric oxide (NO), which goes on to react with, and destroy, ozone ( $O_3$ ).<sup>132</sup> An article by Ravishankara et al. in the journal *Science* calculates the contributions of various ozone-destroying substances, including chlorofluorocarbons (CFCs), halons, methyl bromide, and nitrous oxide and reports that " $N_2O$  emission currently is the single most important ozone-depleting emission and is expected to remain the largest throughout the 21<sup>st</sup> century."<sup>133</sup>

As a result of the 1987 Montreal Protocol limiting the release of CFCs and similar substances, Earth's ozone layer is slowly recovering (though regional reversals and contrary data are being discovered<sup>134</sup>). Nitrous oxide emissions are slowing any recovery by continuing to destroy ozone. (The Montreal Protocol does not cover  $N_2O$ .) The continued suppression of stratospheric ozone concentrations by

130 Andrew Altieri and Robert Diaz, "Dead Zones: Oxygen Depletion in Coastal Ecosystems (Ch. 24)," in *World Seas: An Environmental Evaluation*, ed. Charles Sheppard, Second Edition (Academic Press, 2019), 454.

131 Galloway et al., "The Nitrogen Cascade," 350.

132 Socolow, "Nitrogen Management and the Future of Food," 6004.

133 A.R. Ravishankara, John Daniel, and Robert Portmann, "Nitrous Oxide ( $N_2O$ ): The Dominant Ozone-Depleting Substance Emitted in the 21st Century," *Science* 326, no. 5949 (2009).

134 Gloria Manney et al., "Record-Low Arctic Stratospheric Ozone in 2020," *Geophysical Research Letters* 47, no. 16 (2020); Qing-Bin Lu, "Observation of Large and All-Season Ozone Losses Over the Tropics," *AIP Advances* 7, no. 12 (2022).

N<sub>2</sub>O creates human health impacts including contributions to skin cancer, immunosuppression, and cataracts.<sup>135</sup> Globally, these conditions affect millions of people per year. While only a minor portion of the cases can be attributed to N<sub>2</sub>O and even a smaller portion to fertilizer, even this fraction would equate to large numbers overall.

## Atmosphere: Ammonia, nitrogen oxides, particulate matter, low-level ozone, and human health

According to the World Health Organization, air pollution is responsible for one in eight premature deaths worldwide.<sup>136</sup> While that portion is higher in countries such as India and China and much lower in countries such as Canada, air pollution and its health impacts nonetheless remain major concerns (see Canadian statistics, below).

Fertilizer use contributes to the creation of air pollution and “smog” that, globally, kill more than 3.3 million people annually.<sup>137</sup> The mechanisms of harm are many and complex and include:

**Ammonia (NH<sub>3</sub>).** Ammonia emissions are a significant contributor to the creation of fine particulate matter (e.g., PM<sub>2.5</sub>: particles smaller than 2.5 micrometres). Losses of fertilizer nitrogen as ammonia into the atmosphere can equal 10 to 15 percent of initial N content.<sup>138</sup> A 2014 article notes that agriculture is “the largest source of NH<sub>3</sub> to the atmosphere with important consequences for human health, ecosystems, and climate.... The most costly impact, human health, is due to the production of fine inorganic particulate matter (PM<sub>2.5</sub>) ... a well-documented factor in premature mortality....”<sup>139</sup>

Agriculture and Agri-Food Canada (AAFC) notes that, in this country, “Since 1981, [ammonia] emissions from nitrogen fertilizer have more than doubled (from 58 kilotonnes of ammonia in 1981 to 143 kilotonnes of ammonia in 2016). Livestock-related emissions peaked in, and have been decreasing since, 2006”<sup>140</sup> (partly as a result of a shrinking cattle herd). Federal department Environment and Climate Change Canada (ECCC) notes that “in Canada, agriculture contributes about 85% of the total anthropogenic NH<sub>3</sub>....”<sup>141</sup> Fertilizer use still contributes less ammonia to the atmosphere than does livestock production, but as noted above, the bulk of N-related emissions from livestock can be interpreted as downstream emissions from nitrogen fertilizer since: 1. Most of the N atoms in those livestock-related NH<sub>3</sub> emission molecules come from fertilizer factories; and 2. Without the availability of millions of tonnes of nitrogen fertilizer and the feedgrains produced by that fertilizer, livestock numbers would be a fraction of current levels, as would be livestock-related ammonia emissions from manure. Thus, nitrogen fertilizer use drives up ammonia emissions both from soils and from manure.

ECCC states that “the loss of NH<sub>3</sub> ... represents the loss of a critical nutrient which must be replaced by expensive inputs. Canada-wide, the loss of 371,000 tonnes (t) of NH<sub>3</sub> (306,000 t of N) from farms in

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135 Wolfe and Patz, “Reactive Nitrogen and Human Health,” 124.

136 Maya Almaraz et al., “Agriculture Is a Major Source of NO<sub>x</sub> Pollution in California,” *Science Advances* 4 (2018): 1.

137 Johannes Lelieveld et al., “The Contribution of Outdoor Air Pollution Sources to Premature Mortality on a Global Scale,” *Nature* 525, no. 7569 (2015): 367.

138 Fabien Paulot and Daniel Jacob, “Hidden Cost of U.S. Agricultural Exports: Particulate Matter from Ammonia Emissions,” *Environmental Science & Technology* 48, no. 2 (2014): 904; Houlton et al., “Intentional versus Unintentional Nitrogen Use in the United States,” Fig 4; Bouwman, Brecht, and Van der Hoek, “Global and Regional Surface Nitrogen Balances in Intensive Agricultural Production Systems for the Period 1970-2030,” 145.

139 Paulot and Jacob, “Hidden Cost of U.S. Agricultural Exports,” 903.

140 Agriculture and Agri-Food Canada, “Agricultural Ammonia Indicator,” July 11, 2016, <https://agriculture.canada.ca/en/agriculture-and-environment/climate-change-and-air-quality/agricultural-ammonia-indicator>.

141 Lucy Clearwater, Tim Martin, and Terrie Hoppe, “Environmental Sustainability of Canadian Agriculture,” Agri-Environmental Indicator Report Series—Report 4 (Ottawa: AAFC, 2016), 180.

2011 is equivalent to approximately 15% of all the fertilizer N shipped to farms that year, which translates into an economic cost of around \$400 million....”<sup>142</sup>

Scientists predict that a warming atmosphere will significantly increase ammonia emissions and that the combination of warming plus increased population and crop production and fertilizer use may cause global NH<sub>3</sub> emissions to double this century.<sup>143</sup>

**Nitrogen oxides (NO, NO<sub>2</sub>, NO<sub>x</sub>).** Nitrogen oxides are a significant contributor to air pollution, which is a leading cause globally of human mortality, ecosystem damage, and biodiversity loss.<sup>144</sup> NO<sub>x</sub> contributes to three important types of air pollution: particulate matter (PM<sub>2.5</sub>), ozone (O<sub>3</sub>), and NO<sub>x</sub> itself, via direct inhalation.<sup>145</sup> Also, NO<sub>x</sub> and NH<sub>3</sub> interact and combine to create particulate matter.<sup>146</sup>

While NO<sub>x</sub> is often understood as originating from fossil-fuel combustion, agricultural soils are also a significant source—in some areas, the dominant source.<sup>147</sup> In a 2018 journal article, Almaraz et al. note “similarities in the magnitude of NO<sub>x</sub> emissions from fossil fuel combustion and soil, with the largest soil emissions from regions with heavy N fertilizer applications.”<sup>148</sup>

Near the Earth’s surface, Ozone (O<sub>3</sub>) is both a pollutant and also a component of smog, which damages human health and contributes to millions of premature deaths each year worldwide. “Nitrogen constitutes a major source of O<sub>3</sub> precursor emissions: 60 per cent of the O<sub>3</sub> increase since 1900 is due to an increase in NO<sub>x</sub>....”<sup>149</sup> Low-altitude ozone can cause or exacerbate asthma, respiratory disease and infections, and cardiopulmonary deaths.<sup>150</sup>

Particulate matter (PM<sub>2.5</sub>) causes millions of deaths annually worldwide via several mechanisms including cardiovascular disease, respiratory diseases, asthma, and reduced lung function.<sup>151</sup>

Health Canada estimates that air pollution (notably NO<sub>2</sub>, PM<sub>2.5</sub>, and O<sub>3</sub>) “contributes to 15,300 premature deaths per year in Canada....” and that “nonfatal health outcomes include 2.7 million asthma symptom days and 35 million acute respiratory symptom days per year, with the total economic cost of all health impacts attributable to air pollution for the year being \$120 billion (2016 CAD).”<sup>152</sup>

Just for scale, though the two numbers are *not* directly comparable, that \$120 billion annual cost for air pollution can be seen relative to the \$75 billion gross value of all agricultural products in Canada and a “value add” from fertilizer of just a fraction of that \$75 billion. We cannot proceed without fertilizers, but numerous studies conclude that as fertilizer rates and tonnage rise, benefits taper off

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142 Clearwater, Martin, and Hoppe, “Environmental Sustainability of Canadian Agriculture,” 183.

143 Mark A. Sutton et al., “Towards a Climate-Dependent Paradigm of Ammonia Emission and Deposition,” *Philosophical Transactions: Biological Sciences* 368, no. 1621 (2013).

144 Almaraz et al., “Agriculture Is a Major Source of NO<sub>x</sub> Pollution in California,” 1.

145 Erisman et al., “Consequences of Human Modification of the Global Nitrogen Cycle,” July 5, 2013, Table 1.

146 Erisman et al., “Consequences of Human Modification of the Global Nitrogen Cycle,” July 5, 2013, page 2 and Table 1.

147 Lyatt Jaeglé et al., “Global Partitioning of NO<sub>x</sub> Sources Using Satellite Observations: Relative Roles of Fossil Fuel Combustion, Biomass Burning and Soil Emissions,” *Faraday Discussions* 130 (2005); Almaraz et al., “Agriculture Is a Major Source of NO<sub>x</sub> Pollution in California.”

148 Almaraz et al., “Agriculture Is a Major Source of NO<sub>x</sub> Pollution in California,” 1.

149 Erisman et al., “Consequences of Human Modification of the Global Nitrogen Cycle,” 2013, 6.

150 Townsend et al., “Human Health Effects of a Changing Global Nitrogen Cycle”; Erisman et al., “Consequences of Human Modification of the Global Nitrogen Cycle,” 2013.

151 Townsend et al., “Human Health Effects of a Changing Global Nitrogen Cycle,” 242; Lelieveld et al., “The Contribution of Outdoor Air Pollution Sources to Premature Mortality ....”

152 Health Canada, “Health Impacts of Air Pollution in Canada: Estimates of Premature Deaths and Nonfatal Outcomes, 2021 Report” (Ottawa: Health Canada, 2021), 4.

but harms increase.<sup>153</sup> We should continue using fertilizers, but we should scale back so that the positives far outweigh the negatives. Limits sometimes mean that we get less of what we want, but limits can also mean we get a *lot* less of what we *don't* want: in this case, death and suffering.

Again, not all ammonia (NH<sub>3</sub>) and nitrogen oxides (NO<sub>x</sub>) come from agriculture and not all agricultural pollution emissions are from fertilizer—a great deal comes from livestock manure (though these are multiplied as a result of fertilizer use). Smog, low-level ozone, and other human-health threats have many sources, with fertilizer being just one. That said, the human health harms and environmental impacts are of such a huge magnitude (e.g., contributions to thousands of premature deaths annually in Canada and millions worldwide) that even if nitrogen fertilizer is just one contributor among many, it is a contribution to an extremely large pool of harms. And agriculture is not a minor contributor. An article in the journal *Nature* notes that “Agriculture ... has a remarkably large impact on PM<sub>2.5</sub>, and is the leading source category in Europe, Russia, Turkey, Korea, Japan and the Eastern USA....”<sup>154</sup>

Galloway notes that global emissions of NH<sub>3</sub> have tripled since pre-industrial times (1860 vs. 1993) and will double again by 2050 (1993 vs. 2050).<sup>155</sup> And as fossil fuel combustion in automobiles and electricity generation declines, agricultural emissions will contribute a larger portion of NH<sub>3</sub> to PM<sub>2.5</sub> and make an increasingly large contribution to the toll of deaths and hospitalizations.

Nitrogen fertilizer brings enormous benefits: expanded food and protein supplies and, as a result, greater resistance to infections and even improved educational outcomes. But beyond a certain point, the benefits plateau then decline while the costs and damage continue to mount. In their paper entitled “Human Health Effects of a Changing Global Nitrogen Cycle,” the authors conclude that “the greatest net benefits are found at low to moderate levels of N use, and continued environmental N enrichment will greatly amplify the health costs.”<sup>156</sup> This is another way of stating the importance of maximizing net benefits of fertilizer use rather than attempting to maximize crop yield and output. Many reasons exist to reduce nitrogen fertilizer use, and these include increased net farm income, ecosystem protection, slowing of climate change, and protecting human health and saving lives.

## Atmosphere: Global warming

As detailed in Chapter 3, synthetic nitrogen fertilizer use intensifies climate change. Indeed, nitrogen fertilizer is a major source of *all three* of the main GHGs: carbon dioxide, from its production; nitrous oxide, from its use; and methane, from its natural gas feedstock. Worth noting is that those climate impacts have knock-on effects in terms of human health and ecosystem damage.

Climate change will increase human mortality by many mechanisms, including:

- famine due to crop failures caused by drought and other climate disruptions;
- heat waves, affecting cities and other settlements;
- severe storms and floods, including increasingly intense hurricanes and typhoons;
- sea level rise and subsequent submersion (or degradation by seawater) of many highly productive agricultural areas including river deltas and coastal lowlands;

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153 Townsend et al., “Human Health Effects of a Changing Global Nitrogen Cycle,” 240.

154 Lelieveld et al., “The Contribution of Outdoor Air Pollution Sources to Premature Mortality ....,” 368–69; See also Lina Luo et al., “Integrated Modeling of U.S. Agricultural Soil Emissions of Reactive Nitrogen and Associated Impacts on Air Pollution, Health, and Climate,” *Environmental Science & Technology* 56, no. 13 (2022).

155 Galloway et al., “Nitrogen Cycles,” Table 2.

156 Townsend et al., “Human Health Effects of a Changing Global Nitrogen Cycle,” 244.

- forest fires increased in number and severity;
- exacerbated air pollution and susceptibility to same;
- increases in waterborne and vector-borne infectious diseases;
- water scarcity (for drinking, irrigation, livestock watering, food preparation, washing and hygiene, firefighting, industrial and power-generation cooling, hydroelectricity, etc.);
- forced migrations; and
- wars and revolutions (resulting from crop failures, water disputes, migrations, food-price spikes, economic collapses, etc.).

Via famine, flood, heat, drought, storms, disease, and war, climate change (to which fertilizer-related emissions contribute) will likely kill hundreds of millions of people this century.

One final note about GHG emissions and climate change: It should go without saying, but *fossil fuel combustion is the biggest problem, by far*. Every sector needs to do its part as the world transitions to near-zero emissions by 2050, so nitrous oxide and methane emissions from agriculture must be reduced. But nothing in this report should decrease the urgency of tackling the primary problem: carbon dioxide emissions from fossil fuel use.

## Nitrogen cascade: Conclusion

The preceding list of environmental and health impacts is bleak—even dire. Many may react skeptically, believing the list to be alarmist. It is not. This chapter simply details the proposition that when it comes to nitrogen production, humans have pushed far past planetary limits—strayed far outside the safe operating space for Earth. The preceding is a catalogue of some of the many effects that one should *expect* when we learn that humans have *multiplied* the flow of reactive nitrogen—perhaps the most important nutrient in terms of shaping ecosystems. Humans have intervened massively, using fossil fuels and industrial factories to pour tens-of-millions of tonnes of highly reactive nitrogen into the biosphere; the preceding is a tour of the collateral damage.

Crucial to understand: The negative effects detailed above are not the *unavoidable* results of fertilizer and other forms of reactive nitrogen; they are the results of overuse and hyper-supply. Each of the reactive nitrogen compounds examined above ( $\text{NH}_3$ ,  $\text{NO}_x$ ,  $\text{N}_2\text{O}$ ,  $\text{NO}_3^-$ , etc.) occur naturally. Pristine, pre-industrial (even pre-human) ecosystems cycled millions of tonnes of ammonia, nitrogen oxides, nitrous oxide, nitrate, etc. But those biologically active compounds were in balance with their ecosystems.

Reactive nitrogen is not a toxin: it is crucial to life and to healthy ecosystems. Only when nitrogen is massively oversupplied into those same systems does it trigger a cascade of problems. We must throttle back our megatonne flows. Dr. Wim de Vries informs us that “population exposure to  $\text{PM}_{2.5}$  can be reduced by about 75% relative to 2015 by ambitious policies on pollution control, related to both energy and agricultural production, thus avoiding a large share of the current 3 [to] 9 million premature deaths [globally]....”<sup>157</sup>

The scale of the impacts is huge: millions of lives shortened and nearly every square metre of Earth’s land and water impacted. But huge also are the potentials to slash those impacts. We must make choices, and in making those choices we must be guided by long-term thinking and respect for planetary limits.

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157 de Vries, “Impacts of Nitrogen Emissions on Ecosystems and Human Health,” 5.

## 9. The many benefits of nitrogen fertilizer

*This is a basic problem, to feed 6.6 billion people. Without chemical fertilizer, forget it. The game is over.*

—Norman Borlaug, Nobel Prize winner and father of the Green Revolution.<sup>158</sup>

*From 1960–2010, the population of Earth has more than doubled, yet the amount of land devoted to farming has remained almost the same. How is it possible to feed twice as many people from nearly the same amount of land? The answer is agricultural productivity. ... Agricultural productivity made it possible to save over four million square miles of land that can be left in a natural state or used for other purposes.*

—“Feeding the World & Protecting the Environment,” A high school science resource.<sup>159</sup>

*Continued, affordable access to fertilizer and advanced agricultural techniques can reverse declining soil fertility and prevent chronic crop failures. Farmers employing these methods help their communities feed themselves, feed others and attain greater economic security.*

—CF Industries, North America’s largest producer of nitrogen fertilizer.<sup>160</sup>

### Benefits

The benefits of nitrogen fertilizer are so well-known and so often cited that only a brief listing is needed here. Nitrogen fertilizer contributes to, or at least *could* contribute to, the following benefits:

1. **Feeding the hungry.** Fertilizers (along with the herbicides and insecticides that come as part of the Green Revolution package) have increased food production and decreased hunger, famine, and death. Fertilizers help “feed the world.” Better nutrition creates secondary benefits, including disease resistance and improved educational outcomes.
2. **Reducing food prices.** As noted above, farmers’ use of fertilizers increases grain supplies and thus decreases farmgate and bulk commodity prices (although in many countries the data clearly shows that reductions in farmers’ prices are not passed on to consumers<sup>161</sup>).
3. **Land sparing and reductions in natural ecosystem destruction.** By increasing per-acre yields, fertilizer enables us to grow a given amount of food on less land, thereby creating the potential to limit farmland expansion and preserve natural areas, including forests and jungles.
4. **Erosion control.** Increased biomass tonnage can mean increased plant cover and crop residues, reducing wind and water erosion. In turn, this can reduce siltation in lakes and rivers.
5. **Economic activity, employment, and growth.** Global food production and processing systems create trillions of dollars of revenues and hundreds of millions of jobs. These sectors would be much smaller if there were no fertilizers, because human populations would be much smaller.

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158 Keith Bradsher and Andrew Martin, “Shortages Threaten Farmers’ Key Tool: Fertilizer,” *The New York Times*, April 30, 2008, sec. Business, <https://www.nytimes.com/2008/04/30/business/worldbusiness/30fertilizer.html>.

159 “Feeding the World & Protecting the Environment,” A high school environmental science teacher supplemental resource (Washington, D.C.: Nutrients for Life Foundation, 2015), 3, <https://nutrientsforlife.ca/resources/feedingtheworld/Feeding%20the%20World%20Protecting%20the%20Environment.pdf>.

160 CF Industries, “Corporate Sustainability Report 2012: Helping to Feed the World, Reliably and Responsibly” (Deerfield, IL: CF Industries, 2012), 5, <https://www.cfindustries.com/globalassets/cf-industries/media/documents/reports/sustainability-reports/cf-corporate-sustainability-report-2012.pdf>.

161 “Grocery Prices Are Rising and Farmers’ Share Declining as Corporate Processors and Retailers Take More and More,” News release, National Farmers Union, December 9, 2021, <https://www.nfu.ca/grocery-prices-are-rising-and-farmers-share-declining-as-corporate-processors-and-retailers-take-more-and-more/>.

Nothing in this report should be interpreted as denying the preceding benefits—actual or potential. As noted in the opening pages, nitrogen fertilizer changed the world, multiplying the size of food supplies, human and livestock populations, economies, and cities. If there were no fertilizers and other inputs, many more people may have starved. If there were no fertilizers, we may have had to farm more land, wresting that land from forests and wild areas, further accelerating already apocalyptic rates of species extinction.

## Benefits?

But the preceding is not the same as saying that current rates of fertilizer use are optimal: far from it. Nor is it saying that the *potential* benefits listed above are being maximized or even pursued.

Key to understanding this report is understanding this core idea: **The benefits of nitrogen fertilizer use are real, but so too is the damage it creates, and, as tonnage increases, the benefits taper off while the damage and harms continue to increase, perhaps exponentially—eventually overwhelming the benefits and pushing the overall effect of nitrogen use into net negative territory. Thus, one can be a staunch advocate for fertilizer, yet equally firm in believing that much less should be used.** Indeed, all responsible people who look at the evidence should be expected to take exactly that position. Only ideologues, the techno-enrapt, reckless free-marketers, and agribusiness managers and shareholders should be expected to assert that we should deploy even more reactive N into an already nitrogen-saturated biosphere. Yet that is exactly the course we are on.

Moreover, even if one believes that we are creating benefits at one stage of our food system—e.g., by sowing fertilizer into fields to produce more grain that could feed more hungry people—one would have to look critically at what we are doing with those expanded harvests. On a huge scale, we are *undoing* the benefits. We are turning the potentially life-giving bounty of our fertilizer-expanded harvests not into meals for the hungry, but instead into fuel for SUVs and, soon, for vacation jets and cruise ships; we are landfilling billions of tonnes of wasted food each year; and we are turning billions more tonnes into livestock feedgrain and pushing that into systems that turn five Calories or units of protein into one. Fertilizer cannot be assessed narrowly, merely in terms of expanded crop output tonnage. Rather, it must be assessed in complete social, economic, human-health, and environmental contexts—indeed, a *civilizational* context. When that occurs, we see that other links in the system negate, squander, and reverse the very real benefits fertilizer could otherwise deliver.

The appropriate question is not: Do fertilizers bring benefits? The question must be: Do fertilizers bring *net* benefits? And, even more appropriately: **What is the optimal level of use so as to maximize net benefits?** Maximum net benefit does not correlate with maximum use or maximum yield, especially if those maximized yields are subsequently squandered.



## 10. Government policies are driving up fertilizer use and emissions

*From 1981 through to about 1991 our trade numbers were hovering in the range of about \$10 billion per year. Then beginning in the early 1990s the numbers started to rise quite significantly. The number for 1995 is especially good news. It's \$17.3 billion worth, an all-time record for the value of Canadian agriculture and agri-food trade in the world. The arrow at the end of the chart [not shown here] shows where we are heading as a minimum goal: to reach \$20 billion in agri-food exports by the year 2000. ... Quite frankly, I would like our goal to be a little more ambitious[:] \$23 billion by 2000....*  
—Honourable Ralph Goodale, Minister of Agriculture, 1996.<sup>162</sup>

*The Government of Canada is undertaking the most ambitious trade-expansion plan in Canadian history. ... Re-opening, maintaining and expanding market access for Canadian agriculture and agri-food products is an important part of our plan. With annual exports worth over \$40 billion in 2011, the agriculture and agri-food sector is a key driver of Canada's economy.*  
—Agriculture and Agri-Food Canada (AAFC), 2012.<sup>163</sup>

*To support Canada's farmers and food processors, Budget 2017 sets an ambitious target to grow Canada's agri-food exports to at least \$75 billion annually by 2025.*  
—Agriculture and Agri-Food Canada (AAFC), 2017.<sup>164</sup>

*Canada's agriculture and agri-food exports have continued to increase ..., reaching over \$82 billion in 2021 and surpassing a previous target to grow agri-food exports to at least \$75 billion by 2025.*  
—Agriculture and Agri-Food Canada (AAFC), 2022.<sup>165</sup>

*In the wake of the conflict in Ukraine, our farmers are being called upon to play an even greater role in feeding the world....*  
—Honourable Marie Claude Bibeau, Minister of Agriculture, 2022.<sup>166</sup>

The yield, output, and input-use treadmills that underpin continually rising agricultural emissions and environmental impacts are largely the creation of the globally dominant agribusiness corporations—those that profit from ever-rising grain and livestock production and those that profit from ever-rising input sales. But aligned governments also spur farmers to run on those treadmills. Notably, the Canadian federal government has been very aggressive in pushing farmers to run ever faster.

If Canadian agricultural policy has a Prime Directive, it is this: Increase exports! The federal government and its agriculture department have repeatedly set ever-higher targets for exports. In addition to the quotes above, these targets from AAFC's 2022–23 Departmental Plan<sup>167</sup> are revealing:

162 "Parliament of Canada, House of Commons Standing Cmtee on Ag., Presentation by Minister of Agriculture Ralph Goodale," March 26, 1996, [https://www.parl.ca/Content/Archives/Committee/352/agfo/evidence/07\\_96-03-26/agfo07\\_blk-e.html](https://www.parl.ca/Content/Archives/Committee/352/agfo/evidence/07_96-03-26/agfo07_blk-e.html).

163 Agriculture and Agri-Food Canada, "Agriculture and Agri-Food Market Access Report 2011–2012: Re-Opening, Maintaining and Expanding Markets" (Ottawa: AAFC, 2012), [http://www5.agr.gc.ca/resources/prod/doc/pdf/mar-ram\\_2011-12\\_eng.pdf](http://www5.agr.gc.ca/resources/prod/doc/pdf/mar-ram_2011-12_eng.pdf).

164 Agriculture and Agri-Food Canada, "Budget 2017 Supports Canada's Agriculture and Agri-Food Sector as an Important Driver of Economic Growth," Agri-Info news service, May 4, 2017, <https://www5.agr.gc.ca/eng/news-from-agriculture-and-agri-food-canada/agri-info/budget-2017-supports-canada-s-agriculture-and-agri-food-sector-as-an-important-driver-of-economic-growth/?id=1566594901322>.

165 Agriculture and Agri-Food Canada, "Government of Canada Invests Over \$2.7 Million to Grow Agri-Food Exports," news release, June 9, 2022, <https://www.canada.ca/en/agriculture-agri-food/news/2022/06/government-of-canada-invests-over-27-million-to-grow-agri-food-exports.html>.

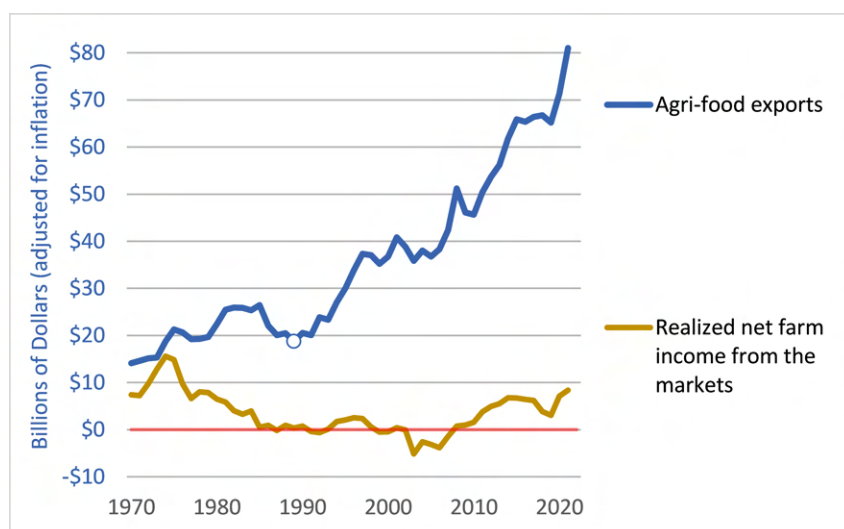
166 Agriculture and Agri-Food Canada, "Government of Canada Invests Over \$1.6 Million in New Technology for High-Efficiency Fertilizers," news release, July 4, 2022, <https://www.canada.ca/en/agriculture-agri-food/news/2022/07/government-of-canada-invests-over-16-million-in-new-technology-for-high-efficiency-fertilizers.html>.

167 Agriculture and Agri-Food Canada, "Departmental Plan 2022–23" (Ottawa: AAFC, 2022), 15.



- “Percentage change in agri-food products sold: At least 4.5%.” A 4.5 percent annual compound growth rate will lead to a doubling every 16 years.<sup>168</sup> Maintaining that rate, say, for a century would lead to six doublings: a 64-fold increase (2, 4, 8, 16, 32, 64). While AAFC has not said that it plans to hold to this pace for an entire century, nonetheless this long-term analysis is revealing: Growth rates that seem reasonable in the short term are exposed as impossible in the long.
- “Value of agri-food exports: At least \$75 billion in 2025.” Already accomplished, this represents a doubling since 2010. If this rate (a doubling every 12 years) were to continue for a century, agri-food exports would double 8 times, leading to a 256-fold increase by 2122: \$20 trillion per year in today’s dollars, which is ten times higher than current Canadian GDP.

As noted, this \$75 billion export target is just the latest in a long series set by the federal government and met by farmers. Figure 14 shows the accelerating increase in Canadian agri-food exports. The graph also highlights the disconnect between export values and farmers’ net returns: the manyfold increase in exports is not mirrored by a similar multiplication in net incomes.



**Figure 14. Canadian agri-food exports and realized net farm income from the markets, 1970 – 2021.**

Sources: Statistics Canada and Agriculture and Agri-Food Canada.<sup>169</sup>

Note: The blue circle at 1989 marks the start of the “free trade” era: the Canada-US Free Trade Agreement.

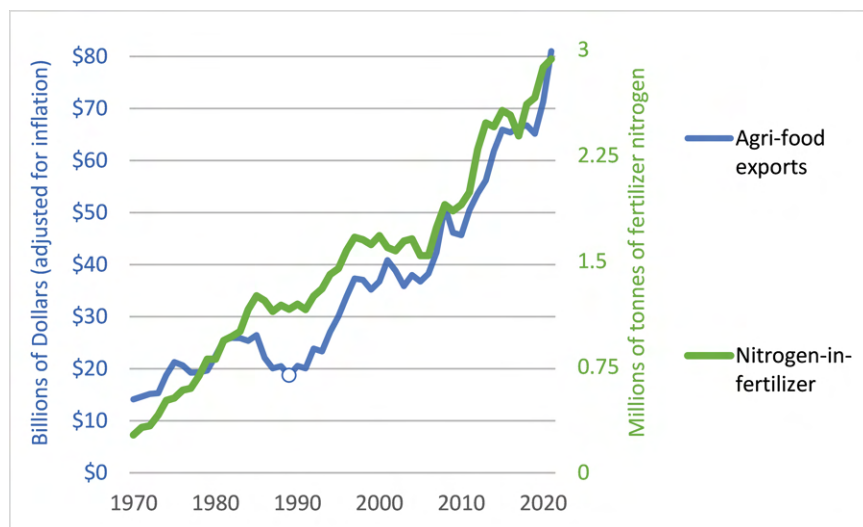
The yield/production/exports/inputs/emissions treadmill on which farmers now run was constructed as a collaborative project of government and corporate leaders. As long as the Prime Directive coming from Ottawa (and embedded in farm programs and policies) is “Produce and Export More,” fertilizer use and resultant emissions and environmental impacts will continue to trend upward.

Some may object that agri-food exports are more than just raw grains: such exports include processed foods, etc. Therefore, pushing for increased agri-food exports need not inescapably lead to increased nitrogen fertilizer use. Granted. But while true in theory, when we look at the actual data over the past

<sup>168</sup> A shortcut for calculating doubling times is “the rule of 70.” Take 70 and divide it by the percentage growth rate and the result is the doubling time. A 10% compound annual growth rate will lead to a doubling every 7 years ( $70 \div 10$ ). A 4.5% rate will lead to a doubling every 16 years ( $70 \div 4.5$ ).

<sup>169</sup> Realized net farm income from the markets (i.e., with farm-support payments subtracted out): Statistics Canada Tables 32-10-0045-01, 32-10-0052-01, and 32-10-0106-01; Agri-food exports: Data from AAFC upon request (from [aa.fc.info@service.aac@canada.ca](mailto:aa.fc.info@service.aac@canada.ca)) and 2021 value from Agriculture and Agri-Food Canada, “Government of Canada Invests Over \$2.7 Million to Grow Agri-Food Exports.”

half century, we see a provocative correlation between exports and consumption of nitrogen-in-fertilizer—suggesting that the drive to increase the former also spurs increases in the latter.



**Figure 15. Canadian agri-food exports and consumption of nitrogen-in-fertilizer, 1970 – 2021.**

Sources: See Figure 7 (page 21) and Figure 14 (page 45).

Is the federal agriculture department focused solely on exports? No and yes. The federal government seems to have other agricultural priorities. For example, in recent years, the government has repeatedly mentioned its intention to create a “Canadian Agri-Environmental Strategy” (which it interchangeably refers to as a “Green Agricultural Plan”).<sup>170</sup> This would be a positive step—perhaps tempering the mania for exports and exponential growth. Clearly, however, the preceding catalogue of human health and ecosystem impacts (see Ch. 8) is wholly incompatible with notions of “environmental” or “green” or “sustainable.” Any “green” plan or “environmental” strategy that did not include strong measures to reduce fertilizer use and the negative impacts from same would be a farce. Governments are clearly looking for incremental or “bolt-on” solutions to the GHG and other environmental problems of agriculture. But the massive extent of the problem, including the tripling of global N flows and the manyfold increase in livestock animal numbers, underscores the need for fundamental transformation. An Agri-Environmental Strategy that plays out alongside rising emissions and other impacts could only be seen as profoundly *anti*-environmental.

Often said: Infinite economic growth within a finite planet is impossible. Most who hear that idea acknowledge that the growth will have to end at some point. We have reached that point. As the Canadian government lays the policy foundations for agriculture in the 21<sup>st</sup> century, it must focus intently on this crucial question: How do we create prosperity, stability, dignity, intergenerational and interspecies justice, and maximal human health and thriving as we assist farmers and the Canadian economy to step off the growth and emissions treadmills?

170 Environment and Climate Change Canada, “A Healthy Environment and a Healthy Economy: Canada’s Strengthened Climate Plan to Create Jobs and Support People, Communities and the Planet” (Ottawa: ECCC, December 2020), 55, [https://www.canada.ca/content/dam/eccc/documents/pdf/climate-change/climate-plan/healthy\\_environment\\_healthy\\_economy\\_plan.pdf](https://www.canada.ca/content/dam/eccc/documents/pdf/climate-change/climate-plan/healthy_environment_healthy_economy_plan.pdf); Government of Canada, “Fall Economic Statement 2020: Supporting Canadians and Fighting COVID-19,” 2020, 89, <https://www.budget.gc.ca/fes-eea/2020/report-rapport/FES-EEA-eng.pdf>; “Minister of Agriculture and Agri-Food Mandate Letter 2021,” Prime Minister of Canada, December 15, 2021, <https://pm.gc.ca/en/mandate-letters/2021/12/16/minister-agriculture-and-agri-food-mandate-letter>; Agriculture and Agri-Food Canada, “Discussion Document: Reducing Emissions Arising from the Application of Fertilizer in Canada’s Agriculture Sector,” March 4, 2022, <https://agriculture.canada.ca/en/about-our-department/transparency-and-corporate-reporting/public-opinion-research-and-consultations/share-ideas-fertilizer-emissions-reduction-target/discussion-document-reducing-emissions-arising-application-fertilizer-canadas-agriculture-sector>; Agriculture and Agri-Food Canada, “Departmental Plan 2022-23,” 5,20.

## 11. Corporate control of fertilizer production and prices

*A significant horizontal and vertical restructuring is underway across food systems. A spate of mega-mergers is sparking unprecedented consolidation in the seed, agri-chemical, fertilizer, animal genetics and farm machinery industries....*

—Pat Mooney and The International Panel of Experts on Sustainable Food Systems.<sup>171</sup>

*In effect, these corporations are stealing the farmers' profits. ... If these corporations are tying the price of their products to the farmer's ability to pay, rather than to supply and demand, that equates to an abuse of the market. Such abuses allow concentrated corporations to extract maximum profit out of the supply chain....*

—Sarah Carden et al. and Farm Action, "Big Fertilizer."<sup>172</sup>

*We have seen record price spikes that are not reflective of increased production costs, but instead indicative of industry-wide collusive pricing behaviors and profiteering. ... Recent record-breaking fertilizer prices coincided suspiciously with an increase in income farmers were earning from commodity crops. While fertilizer corporations claimed these prices were the result of shortages and high natural gas prices, their own annual and quarterly reports refuted these claims.*

—Farm Action and 23 US farm, food, and rural organizations.<sup>173</sup>

*Collusive agreements between fertilizer producers on prices and market shares pepper the history of the global commercial fertilizer industry dating back to the 1880s. The underlying structure of the current global industry remains conducive to anticompetitive coordination—a landscape that undoubtedly prompted Wall Street Journal commentators to observe that fertilizer markets are so manipulated, "they might make a Saudi prince blush".... A 1949 report by the [US] Federal Trade Commission (FTC), for example, documents cartels in nitrogen, phosphorus, and potash from before World War I to just after World War II. Connor identifies 83 known hard-core international fertilizer cartel episodes over the period 1902 to 2010.... Twenty fertilizer cartels were detected from 1990–2010. Numerous conditions make the fertilizer industry conducive to cartelization, for individual nutrients and all three nutrients together. These factors include: inelastic demand, high barriers to entry, easy explicit and tacit communication between members, and corporate and government control of limited reserves. Observed sustained high profit margins, excess capacity, and the concomitant movement of nitrogen, phosphorus, and potash prices are also consistent with cartel behavior.*

—C. Robert Taylor and Diana Moss, "The Fertilizer Oligopoly"<sup>174</sup> (See footnotes in report.)

We could have written a very different version of this report: one in which the dominant fertilizer corporations are the focus and the villains; one that casts Nutrien Ltd., CF Industries, Yara International, Koch Fertilizer, and other corporations as pushing farmers in Canada and other nations to use ever-

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171 Pat Mooney and International Panel of Experts on Sustainable Food Systems (IPES-Food), "Too Big to Feed: Exploring the Impacts of Mega-Mergers, Concentration, Concentration of Power in the Agri-Food Sector" (IPES-Food, 2017), 5, [http://www.ipes-food.org/\\_img/upload/files/Concentration\\_FullReport.pdf](http://www.ipes-food.org/_img/upload/files/Concentration_FullReport.pdf).

172 Sarah Carden, "Big Fertilizer: Measuring the Impacts of Food and Farm System Concentration," A Special Report by Farm Action Prepared for the U.S. House of Representatives Judiciary Subcommittee on Antitrust, Commercial, and Administrative Law (Farm Action, January 19, 2022), 5.

173 Farm Action and 23 other farm, food, and rural organizations, "Letter to Jaina Nian, Agriculture Marketing Services, USDA," Re: Comments on Access to Fertilizer: Competition and Supply Chain Concerns, June 10, 2022, <https://farmaction.us/wp-content/uploads/2022/06/Farm-Action-Fertilizer-Competition-Comments-6.10.22.pdf>.

174 C. Robert Taylor and Diana Moss, "The Fertilizer Oligopoly: The Case for Global Antitrust Enforcement" (Washington, D.C.: The American Antitrust Institute, September 2013), 7 & 14, <https://www.semanticscholar.org/paper/The-Fertilizer-Oligopoly%3A-The-Case-for-Global-Moss/9c88e501d376fe8a19f9de4a1379c22765f8c965#citing-papers>.

larger amounts of nitrogen fertilizer and thus emit ever-larger quantities of damaging emissions. Yet here we are, only now getting to details of the dominant fertilizer transnationals.

Doubtless, those companies have central and very negative roles. They have pressured governments, created self-serving trade associations, funded political candidates, encouraged farmers to use more fertilizer than necessary, possibly manipulated prices, maximized profit extraction from farmers, and reaped huge rewards by pushing the planet far beyond its safe operating limits. It is beyond the scope of this report to research and detail the past half-century of fertilizer company actions in North America and around the world, but if a researcher or historian were to do so, the result would very likely be a story similar to that of Big Oil, climate change, and the projects of spreading uncertainty and evading regulation. (On those latter subjects, see the excellent *Merchants of Doubt*.<sup>175</sup>)

Fertilizer corporations are certainly major actors, but the prime mover is the logic of the global system: The drive for growth without limit. In all parts of our neoliberal economies—energy use, manufacturing, travel, consumer goods, luxury items—we are focused on doubling and redoubling supply, spending, consumption, and profits. To lay the blame for the doubling and redoubling of fertilizer tonnage and resulting ecological damage at the feet of a few corporations would be intellectually lazy, and would also obscure solutions. Dramatically improving our situation is not dependent on making some corporations “behave better”; it is dependent on recognizing and dealing with *structural* pathologies: a global economic system in which unlimited increases in inputs, resource use, and production are coupled to unlimited increases in consumption, dissipation, waste, unwise uses, and indulgence.

## Market power

The preceding stated, it remains informative to examine the actual structure and conduct of the fertilizer sector and the actions of its dominant corporations. By so doing, we find many more reasons to reduce use and to help farmers reduce dependence on these powerful, profiteering entities. Looking at the structure and conduct of the fertilizer sector helps us see an alternative road whereon less fertilizer use can equal more net farm income.

Key to understanding fertilizer prices and companies is understanding market power. Farmers occupy the middle link in an agri-food chain that stretches from energy companies at one end to retailers and consumers at the other. At the first link in the chain, we find oil and natural gas companies that produce energy and fuels. Moving to the next link, we find fertilizer and chemical companies. Advancing along the chain, we have machinery and seed companies. Forming another link are the banks. All these links together are the “input” or the “upstream” links. At the mid-point is the farmer link, where farmers combine the inputs—energy, fertilizer, pesticides, seeds, technology, machinery, borrowed money, and other capital—with soil, rain, and sun to produce food. Moving beyond the farmer link, we find the “downstream” links: grain companies and commodity traders, railways, food processors, meat packers, brewers and distillers, retailers, and restaurants.

When considered this way, several things stand out. Most apparent: Nearly every link, nearly every sector, is dominated by a few giant transnational corporations (sometimes only two). The exception is the farm link. In Canada, that link is made up of about 200,000 relatively small, often family-owned “firms”—in North America, more than two million. In every other link, firms are huge and competitors few. At the farmer link, firms are small and competitors numerous.

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175 Naomi Oreskes and Erik Conway, *Merchants of Doubt: How a Handful of Scientists Obscured the Truth on Issues from Tobacco Smoke to Global Warming* (New York: Bloomsbury Press, 2010).

How many competitors do the dominant fertilizer companies face? How concentrated is that sector? Economists often look at the market share of the top four companies (also known as the concentration ratio of the top four firms, or CR4). A CR4 of 40 percent is considered high and potentially market distorting: an “oligopoly.”<sup>176</sup> Data from Nutrien Ltd. shows that the Canadian CR4 is 95 to 100 percent (see Table 4). Nutrien, CF Industries, Koch Fertilizer, and Yara wholly dominate Canadian production.

**Table 4. Canadian and US ammonia and urea production capacities and company market shares.**

	Company	Ammonia		Urea	
		Annual tonnes (thousands)	Percent of total	Annual tonnes (thousands)	Percent of total
<b>Canada</b>	Nutrien Ltd.	2,405	44%	1,940	46%
	CF Industries	1,568	29%	1,025	24%
	Koch Fertilizer	548	10%	217	5%
	Yara	682	12%	1,072	25%
	<b>Total Canada</b>	<b>5,485</b>		<b>4,254</b>	
	<b>CR4=</b>		<b>95%</b>		<b>100%</b>
<b>USA</b>	Nutrien Ltd.	2,475	14%	2,140	17%
	CF Industries	7,122	40%	5,868	46%
	Koch Fertilizer	1,844	10%	1,955	15%
	Yara	726	4%		0%
	<b>Total US</b>	<b>17,874</b>		<b>12,886</b>	
<b>Canada and USA</b>	Nutrien Ltd.	4,880	21%	4,080	24%
	CF Industries	8,690	37%	6,893	40%
	Koch Fertilizer	2,392	10%	2,172	13%
	Yara	1,408	6%	1,072	6%
	<b>Total Canada &amp; US</b>	<b>23,359</b>		<b>17,140</b>	
	<b>Market share of 4 selected firms=</b>		<b>74%</b>		<b>83%</b>

Source: Nutrien Ltd.<sup>177</sup>

Fertilizer companies or analysts might object that Canadian CR4s are not accurate measures of competition because fertilizer is traded in a North American market. Granting that contention, we find that when we take US production capacity into account, the four firms that control Canadian production also have a dominant position in the joint Canada-US market, with 74 percent of ammonia capacity and 83 percent for urea (Table 4). (Note that these latter two figures are not CR4s, per se, as they are based on the four firms that dominate Canada and not the four largest in the combined Canada-US market. Nonetheless, North American CR4s would be almost identical: 75 to 85 percent.)

Nutrien, CF Industries, Koch Fertilizer, and Yara exert tremendous market power both in Canada and across North America. They form an oligopoly and thus have potential price-setting and profit-taking powers that simply would not be possible in markets where adequate price-disciplining competition existed.<sup>178</sup> We explore that potential pricing power below.<sup>179</sup>

176 “Four-Firm Concentration Ratio,” Oxford Reference, n.d., <https://doi.org/10.1093/oi/authority.20110803095831707>.

177 Nutrien Ltd., “Nutrien Fact Book 2022,” 17 & 18.

178 Some may argue that fertilizer markets are global, prices are set internationally, and that (relatively modest) North American nitrogen fertilizer imports and exports mean that the proper CR4 boundary is the global market, in which there are more companies and a lower CR4. We find that argument weak. Nonetheless, the NFU would welcome an independent, well-resourced inquiry into the structure and conduct of North American and global fertilizer markets. If it is found that those markets are without price-distorting oligopolies or cartels, the NFU will happily revise future editions of this report.

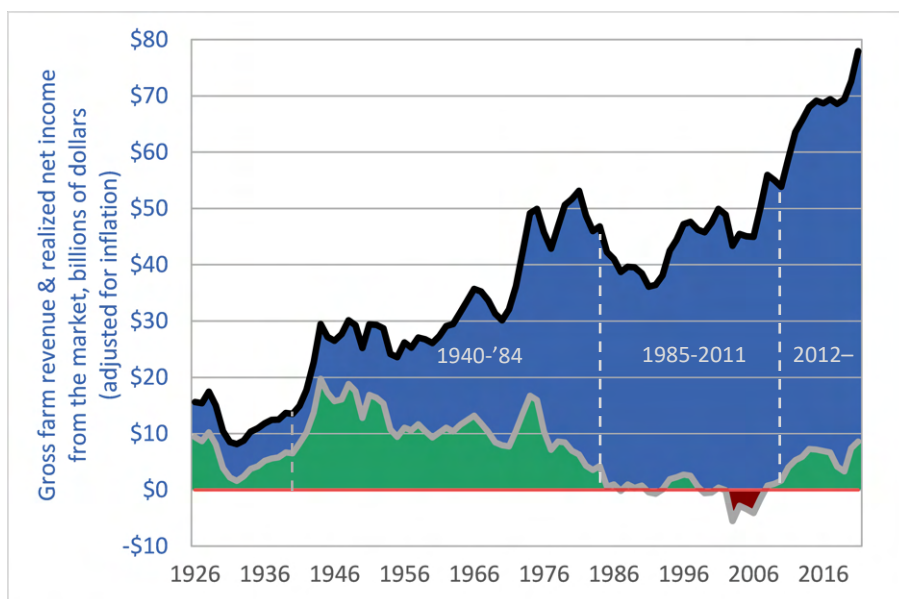
179 Disclaimer: The NFU is not asserting that, and possesses no proof that, any specific corporation or other entity has engaged in activities that are illegal or in contravention of any law or regulation. The NFU is not an investigative body; nor is it expert in competition law or attendant economics. Investigating, documenting, and prosecuting anti-competitive behaviour is the sole purview and jurisdiction of government agencies, and only those agencies can determine that breaches have occurred. Nonetheless, based on several factors and observations, the NFU has concerns and strongly recommends that appropriate government agencies undertake investigations.

Corporate concentration and market power go beyond production capacity to include control of retail: “vertical integration.” To give one example, in addition to its dominant position in fertilizer production,

Nutrien operates the largest global direct-to-grower agricultural retail distribution network.... As of December 31, 2021, Nutrien operated 1,230 retail facilities in the United States, 295 retail facilities in Canada, ... and 414 retail locations in Australia. Nutrien's Retail operations offer farmers a complete range of seed, liquid and dry fertilizer products, primary crop protection products including herbicides, insecticides, fungicides, ... as well as a range of related services and solutions including ... precision agriculture. ... We have approximately 3,900 agronomists and field experts who provide critical advice from the crop planning stage right through to harvest.<sup>180</sup>

## Profit-taking power

Market power determines the allocation of revenues and profits within the agri-food chain. Big players with few competitors have market power; small players with thousands of competitors don't. Looking up and down the agri-food chain, farmers are unique in their lack of market power. And farmers' already-low relative power is declining, eroded by corporate mergers, on the one hand, and the loss of farmers' marketing agencies, on the other. That declining power is a key reason why farmers' margins shrunk from 34 cents per dollar in the 1940-to-1984 period to just 1 cent per dollar in the 26-year period 1985 to 2011 (see Figure 16). During that latter period, which included many years when net incomes from the markets were negative, the markets returned a grand total of \$2.4 billion of realized net farm income, and Canadian taxpayers backfilled with more than \$110 billion in income-support payments (aka Business Risk Management programs). For a quarter century, agribusiness corporations extracted 99 percent of the food wealth produced by Canadian farmers. Farmers were forced to make do on less while others used their growing power to take more. Taxpayers were forced to pitch-in to replace dollars taken by these powerful corporations.



**Figure 16. Canadian gross farm revenue and net income, from the markets, adjusted for inflation, 1926 – 2021.**  
Sources: Statistics Canada Tables 32-10-0045-01, 32-10-0052-01, and 32-10-0106-01.

180 Nutrien Ltd., “Nutrien Fact Book 2022,” 7.



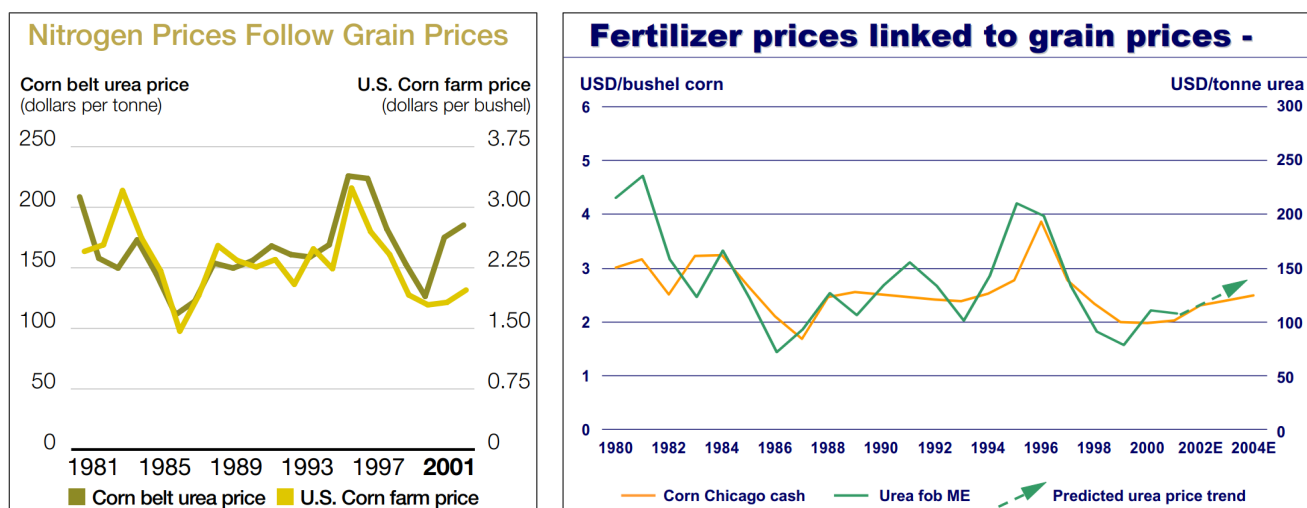
The farm income situation has improved in recent years. Over the past decade (2012 to 2021, inclusive), farmers have managed to hold onto 9 cents out of every dollar they generated (Figure 16). On many farms, this has meant dramatic prosperity. But much of that prosperity can be understood as enlarged farms capturing net incomes that used to support three, five, or ten families. Over the past decade, farmers cropping many thousands or tens-of-thousands of acres have reaped windfalls—often in the millions of dollars.<sup>181</sup>

Despite these pockets of farm wealth, the reality is that over the past two generations, fertilizer corporations and other input manufacturers and sellers have installed themselves as the primary beneficiaries of the wealth farmers create—capturing more than 90 percent of crop and livestock revenues. In the relatively “good times” since 2011, farmers have retained a total of \$62 billion as realized net income from the markets, but input corporations made off with \$650 billion. Over a longer period, farmers’ net incomes from the markets since 1985 total \$65 billion, but the share captured by agribusiness input sellers totals nearly \$2 trillion—thirty times as much.<sup>182</sup> This is not a system working in the interests of farmers or the Canadian nation.

But is this not circumstantial evidence? Might not many explanations exist for farmers’ declining margins? Perhaps, but doubts diminish when we read what the corporations themselves are saying to their shareholders about their market and pricing power.

## Pricing power

Above, this report suggests that, based on low levels of competition (CR4s of 75 to 100 percent), the firms that dominate Canadian fertilizer production and retail (Nutrien, CF Industries, Koch Fertilizer, and Yara) will have significant price-setting powers. Here, we explore that phenomenon.



**Figure 17. Two graphs showing US Corn and nitrogen/urea prices, various years, Agrium and Norsk Hydro.**

Sources: Left graph: Reproduced from Agrium’s 2001 Annual Report;<sup>183</sup> Right graph: Reproduced from Norsk Hydro’s 2002 Capital Market Day presentation.<sup>184</sup>

181 Even during the “good years” post 2011, taxpayers have been providing about one dollar in four of realized net farm income: \$21 billion out of a total of \$84 billion. And over that ten-year period, farm debt has doubled to \$130 billion.

182 All figures adjusted for inflation.

183 Agrium Inc., “2001 Annual Report: Positioned for Success” (Calgary: Agrium, 2002), 15, [https://www.annualreports.com/HostedData/AnnualReportArchive/a/TSX\\_AGU\\_2001.pdf](https://www.annualreports.com/HostedData/AnnualReportArchive/a/TSX_AGU_2001.pdf).

184 “Norsk Hydro ASA Capital Markets Day 2002,” accessed June 11, 2022, <http://reports.huginonline.com/884489/111200.pdf>.



The left-side graph in Figure 17 was produced by Agrium Inc., which merged to form part of Nutrien Ltd., now the world's largest fertilizer company.<sup>185</sup> Agrium/Nutrien is clear: "Nitrogen Prices Follow Grain Prices." Somehow, when grain prices rise, fertilizer prices rise, too. Of course, such outcomes are hard to achieve in markets disciplined by adequate competition. Only because fertilizer companies are large and competitors few do opportunities exist to adjust prices to capture farmers' surpluses (if that is what in fact is happening).

Agrium is not the only fertilizer company to note that fertilizer prices rise when grain prices rise. The right-side graph of Figure 17 is sourced from Norsk Hydro, now known as Yara. Norsk/Yara is more cautious in its language, stating that fertilizer prices are somehow "linked" to grain prices. In 2021 and 2022, farmers are again experiencing that linkage. Much-improved grain prices are occurring at the same time as much higher fertilizer prices. Granted, there is a lot to talk about regarding higher fertilizer prices: Natural gas prices are up; there is war in Ukraine; fertilizer markets are reacting to a reduction in Russian tonnage; and, potentially, farmers with larger past or expected future incomes may be demanding more fertilizer so fertilizer prices may be responding to increased demand. Thus, those who would point to supply and demand and argue against the idea that fertilizer companies may be using their market power and lack of competition to cash in on high grain prices can certainly do so. But the preceding graphs should give such people pause. There is no inconsistency in being a staunch free-marketer or conservative, and also granting that monopolies and oligopolies often lead to prices significantly higher than those that would result from supply and demand in competitive markets. Every economics textbook includes that lesson.

In Yara's 2018 *Fertilizer Industry Handbook*, a section under the heading "Correlation between long-term grain and fertilizer prices" states that "Variations in grain prices (corn or wheat) explain approximately 50% of the variations in the urea price, making grain prices one of the most important factors driving fertilizer prices."<sup>186</sup>

A late-2021 study by Texas A&M economists looked at changes in fertilizer prices in the US and whether they can be best explained by corporate power and profiteering. That report is nuanced and should be examined in its entirety. Nonetheless, an excerpt is revealing:

The suggestion that recent increases in the price of natural gas are the primary reason for recent increases in the prices of nitrogen products is highly suspect. For example, the price of [anhydrous ammonia (AA)] increased \$688 per ton from the end of 2020 through the end of October 2021. However, the increase in the value of the embedded natural gas accounts for only \$102 (or 15%) of that increase. ... Once the value of natural gas in a ton of AA has been subtracted from the AA price, the residual tends to closely track the price of corn, albeit on different scales. This close correspondence could be due to increased demand for nitrogen products as corn prices increase, or could be due to the exercise of market power by nitrogen product manufacturers and extraction of economic rents from corn producers. ... The intent of this brief analysis is to neither prove nor disprove either of those two explanations. But, it does raise serious questions and certainly helps explain the frustration producers are feeling.<sup>187</sup>

185 Nutrien, "Nutrien Fact Book 2020," 10.

186 Yara International, "Fertilizer Industry Handbook 2018" (Oslo: Yara, 2018), 75.

187 Joe Outlaw et al., "Economic Impact of Nitrogen Prices on U.S. Corn Producers" (College Station, TX: Agricultural and Food Policy Center (AFPC), Texas A&M University, December 20, 2021), 10, <https://dt176nijwh14e.cloudfront.net/file/481/Study%20.pdf>.

The economists are saying that, based on their analysis, Agrium/Nutrien might be right: fertilizer prices might follow grain prices. Yara may be right, too: grain prices might be one of the most important factors driving fertilizer prices.

In August 2022, in announcing its second-quarter financial results, Nutrien Ltd. stated that:

Nutrien deliver[ed] record first half earnings and expects strong second half. ... Nutrien generated net earnings of \$5.0 billion and adjusted EBITDA of \$7.6 billion in the first half of 2022 due to higher realized prices and strong Retail performance, more than offsetting a reduction in fertilizer sales volumes. ... Nitrogen second quarter and first half adjusted EBITDA increased compared to the prior year due to higher net realized selling prices that *more than offset higher natural gas costs and lower sales volumes* [italics added].<sup>188</sup>

Nutrien tells us two interesting things: 1. Demand was down, as evidenced by lower sales volumes; and 2. Its price increases were in excess of those needed to cover increased costs such as any higher natural gas prices; hence the company's higher margins and record net earnings. Yara and CF Industries made nearly identical statements.<sup>189</sup>

In December 2021, the President of the US Family Farm Action Alliance sent a letter to the US Department of Justice calling for an investigation into "the alarming spike in prices charged to farmers by highly-concentrated fertilizer corporations." That letter states that "these corporations are using their monopoly power to raise and lower the price charged to farmers not based on basic supply and demand, but rather on the price the farmer is paid for their commodity crops."<sup>190</sup> This analysis is largely shared by Agrium/Nutrien: "Nitrogen Prices Follow Grain Prices."

In a December 2021 letter to the US Attorney General, Republican Senator Charles Grassley calls on the Justice Department to "investigate concerns raised by America's farmers about possible anti-competitive activity and market manipulation in the fertilizer industry" and notes "concerns that fertilizer companies are colluding and unfairly raising the price of their products."<sup>191</sup> Grassley points out that nitrogen production is "heavily concentrated with 75% of the market consisting of four companies."

On January 14<sup>th</sup>, 2022, again on February 24<sup>th</sup>, and again on August 17<sup>th</sup>, Canada's NFU requested that the House of Commons Standing Committee on Agriculture investigate fertilizer pricing. NFU President Katie Ward noted "the absence of any competitive forces acting on the fertilizer companies" and that "the price increases farmers face have little relationship to costs of fertilizer production and distribution."<sup>192</sup> Regrettably, other Canadian farm organizations have been slow to call attention to the potential role played by fertilizer companies in the pricing problem. On March 3<sup>rd</sup>, federal

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188 "Nutrien Delivers Record First Half Earnings and Expects Strong Second Half," News release, Nutrien, accessed August 4, 2022, [www.nutrien.com/investors/news-releases/2022-nutrien-delivers-record-first-half-earnings-and-expects-strong-second](https://www.nutrien.com/investors/news-releases/2022-nutrien-delivers-record-first-half-earnings-and-expects-strong-second).

189 Katie Ward and Stewart Wells, "Letter to Ag Committee Requesting Requesting Fertilizer Investigation," August 17, 2022, <https://www.nfu.ca/letter-to-ag-committee-requesting-fertilizer-investigation/>.

190 Joe Maxwell, President, Family Farm Action Alliance, "Letter to The Honorable Jonathan Kanter, Assistant Attorney General, Antitrust Division Department of Justice, Regarding the Alarming Spike in Prices Charged to Farmers by Highly-Concentrated Fertilizer Corporations," December 8, 2021, [https://farmaction.us/wp-content/uploads/2021/12/FFAA\\_DOJ\\_Fertilizer\\_Investigation\\_Final.pdf](https://farmaction.us/wp-content/uploads/2021/12/FFAA_DOJ_Fertilizer_Investigation_Final.pdf).

191 Charles Grassley, "Letter to US Attorney General Merrick Garland," December 15, 2021, [https://www.grassley.senate.gov/imo/media/doc/grassley\\_to\\_justice\\_dept.fertilizer.pdf](https://www.grassley.senate.gov/imo/media/doc/grassley_to_justice_dept.fertilizer.pdf).

192 National Farmers Union, "NFU Renews Call to Investigate Fertilizer Pricing," Media Release, National Farmers Union, February 24, 2022, <https://www.nfu.ca/media-release-nfu-renews-call-to-investigate-fertilizer-pricing/>; National Farmers Union, "Request for Investigation of Fertilizer Pricing in Canada," Media Release, National Farmers Union, January 14, 2022, <https://www.nfu.ca/request-for-investigation-of-fertilizer-pricing-in-canada/>.

Member of Parliament Kody Blois, Chair of the Standing Committee, stated that the NFU was the only farm group that has approached the Committee about the fertilizer price issue.<sup>193</sup>

## Political power

Fertilizer companies reap tens-of-billions of dollars in global annual revenues. Not surprisingly, these powerful entities have organized to protect themselves politically.

In the US, Political Action Committees (PACs) are entities that collect and pool contributions then donate that money to candidates or to campaigns for legislation. The US industry organization The Fertilizer Institute (TFI) explains its need for a PAC, “FERT PAC,” this way: “Active engagement in the political process is an important means of protecting the fertilizer industry’s interests.”<sup>194</sup> FERT PAC financial contributions supported the election campaigns of “more than 60 members of Congress” and in its election funding, FERT PAC had a “92% Success Rate!”<sup>195</sup>

Entire reports could be written about the lobbying and political efforts by fertilizer companies and their industry associations, including international work at venues such as the COP climate conferences and the UN Food and Agriculture Organization (FAO). Following, we merely list a few of the players:

**Global Alliance for Climate Smart Agriculture (GACSA)** (<https://www.fao.org/gacsa/about/en/>). The organization GRAIN calls the GACSA the “culmination of several years of efforts by the fertiliser lobby to block meaningful action on agriculture and climate change” and notes that “of the Alliance’s 29 non-governmental founding members, there are three fertiliser industry lobby groups [and] two of the world’s largest fertiliser companies....”<sup>196</sup> The GACSA is not an easy organization to understand or characterize. It now comprises more than 500 members and observer organizations; the UN FAO hosts its secretariat; and its pronouncements and structure seem designed to obscure its intentions.

**International Fertilizer Association (IFA)** (<https://www.fertilizer.org/>). The IFA describes itself as a “global fertilizer association [with] a membership of some 400 entities, encompassing companies across the fertilizer value chain from producers through traders and distributors and service providers to advisors, research organizations and NGOs.”<sup>197</sup>

**Fertilizers Europe** (<https://www.fertilizerseurope.com/>). Members include Yara and several other corporate and national association members.

**Fertilizer Canada** (<https://fertilizercanada.ca/>). Fertilizer Canada states that “our members benefit from being in a better position to influence the activities and decisions of governments.” Members include the four companies that dominate Canadian nitrogen production, but also other national and regional industry associations, demonstrating the interlocking and coordinated nature of these groups. For example, members of Fertilizer Canada include Fertilizers Europe, International Fertilizer Association (IFA), and The Fertilizer Institute (TFI). Recently, when the Canadian federal government announced a goal to reduce fertilizer-related GHG emissions by 30 percent by 2030, Fertilizer Canada commissioned a report by Meyers Norris Penny that pushed back hard against the government’s plan.

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193 Sean Pratt, “U.S. Requests Probe into Crop Input Prices,” *The Western Producer*, March 3, 2022, <https://www.producer.com/news/u-s-requests-probe-into-crop-input-prices/>.

194 “FERT PAC,” October 6, 2016, <https://www.tfi.org/policy-center/get-involved/fert-pac>.

195 Clark Mica, Vice President, The Fertilizer Institute, “Political Dynamics Impacting Ag and the Fertilizer Industry,” Slide 23.

196 GRAIN, “The Exxons of Agriculture,” 2.

197 International Fertilizer Association, “About IFA What We Do,” accessed August 21, 2022, [https://www.fertilizer.org/Public/About\\_IFA/What\\_We\\_Do/Public/About\\_IFA/About\\_IFA\\_What\\_We\\_Do.aspx](https://www.fertilizer.org/Public/About_IFA/What_We_Do/Public/About_IFA/About_IFA_What_We_Do.aspx).

**The Fertilizer Institute (TFI)** (<https://www.tfi.org/>). TFI “is the voice of the [US] fertilizer industry”—proudly “taking a stand and having a say in the policies affecting the industry.” Its members include large fertilizer corporations but also other companies. See above regarding its FERT PAC contributions to political campaigns.

**North American Climate Smart Agriculture Alliance (NACSAA)** (<https://www.nacsaa.net/>). The list of “partners” is diverse, but includes Fertilizer Canada, The Fertilizer Institute (TFI), several large fertilizer corporations, CropLife America, the Ontario Federation of Agriculture, and the Canadian Federation of Agriculture (CFA). (Again, various organizations interlock, sometimes recursively, e.g., the CFA lists Nutrien and Fertilizer Canada among its “corporate leaders.”<sup>198</sup>)

**International Fertilizer Development Center (IFDC)** (<https://ifdc.org/>). GRAIN characterizes IFDC as “the main vehicle for the promotion of fertilisers in the South” and notes that “IFDC lobbies governments for policies that increase fertiliser use....”<sup>199</sup> Partners include IFA and TFI.

The preceding list omits a large number of similar regional organizations in Africa, Asia, and South America as well as those that lobby for agribusiness generally.

No sophisticated person will be surprised to learn that a multi-billion-dollar global sector such as the fertilizer industry has multiple interlocking trade associations and lobby groups. However, this information is key to understanding many other aspects of the fertilizer story and how we have come to a place where our use of nitrogen has gone so far past the safe operating limits of Earth and how these companies can capture the lion’s share of wealth created on our farms, with seldom even a polite inquiry from our elected leaders or Canada’s many industry-aligned farm organizations.

## Farmers taking back their power?

In its Preface, this report points out that a key contributor to fertilizer price spikes is that, in a system in which prices are partly set by supply and demand, farmers relentlessly drive up demand. (E.g., see the graph of Canadian fertilizer use, Figure 7, page 21.)

Above, this report documents that after enjoying margins of roughly 34 cents per dollar for much of the postwar period, farmers’ margins have now declined to somewhere between 0 and 10 cents.

Over the past generation (1985 – 2021), Canadian farmers produced nearly \$2 trillion in farm output. Fertilizer companies and other input makers and sellers captured 97 percent of that \$2 trillion. To “keep the wheels on” the farm sector, taxpayers had to contribute \$130 billion in farm-support program funding—*twice as much* net income as was provided by “the markets.” To underscore that last point: Since 1985, two out of three net income dollars have come from taxpayers. And amid all of this, we increased emissions and environmental impacts. The maximum-output, maximum-input model is a failure. And it is a contributor to price spikes and company power. To begin to temper that power and those company profits, farmers have to restrain their ever-rising demand for fertilizers. Farmers have to work together and also work with governments to wholly realign Canadian agriculture. The remaining chapters explore that realignment.

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198 Canadian Federation of Agriculture, “Our Corporate Partner/Leaders,” n.d., <https://www.cfa-fca.ca/about-us/our-corporate-partners/>.

199 GRAIN, “The Exxons of Agriculture,” 4.

A reduction in fertilizer use can lead to a reduction in fertilizer company power and profiteering, and to a reduction in farmer dependency and vulnerability. In turn, this can lead to an increase in farmers' margins, net incomes, autonomy, and security. Though *we can't go back*, looking at recent history shines a spotlight on the shortcomings of our current situation.

**Table 5. Farmers' net income, fertilizer use, and farm numbers, selected periods.**

	Realized net farm income from the markets, adjusted for inflation	Total nitrogen-in-fertilizer tonnage applied over the ten-year period	Number of farms supported, period mid-point
<b>1970–79, inclusive</b>	\$107,265,574,000	5,059,070	338,552
<b>2012–21, inclusive</b>	\$62,747,038,000	25,812,000	193,492

Sources: various Statistics Canada Tables.

We cannot go back. Moreover, Canadian agriculture in the 1970s had its own problems, including tillage, seeding, and summerfallow practices that depleted carbon from soils. But comparing our current situation to the past reveals valuable insights. Most significant: Farmers have increased nitrogen tonnage fivefold and have been rewarded with aggregate net incomes little better than half as much. Those who most steadfastly defend “the markets” should reflect that those markets have not rewarded farmers for their enthusiastic embrace of fertilizers and output maximization. Indeed, the values in the table suggest that productivism and input-maximization have been a trap. Any sector that quintuples its use of a purchased input and finds its net returns half as high would be wise to reflect on its choices and to energetically explore alternatives.

## 12. Responses: The context and big picture

*For every complex problem, there is a solution that is simple, obvious, and wrong.*  
—A paraphrase of H.L. Menken.<sup>200</sup>

For every problem, there exists a range of potential responses that differ in scale and ambition—forming a continuum from incremental to transformative. Are we considering tweaks and techno-add-ons or imagining transforming the system’s foundational goals, practices, and structures?

More concretely, responses to the problems of ever-increasing fertilizer use and resultant impacts can range from minor and simple-to-implement changes such as reduced spreading on the soil surface, to suites of changes that transform the system: linked changes in the crops we grow and the rotations we use; our approaches to fertilizer and yield; the roles of livestock; and our goals and priorities for the system. Table 6 provides notional examples of various scales of changes. This is not a set of recommended changes per se, but rather examples of how different kinds of responses imply different timelines, different levels of ambition, and different probabilities of ongoing success.

**Table 6. Notional examples of different scales and ambition levels.**

	<b>Current</b>	<b>Tweaked</b>	<b>Transformed</b>
<b>Primary goals of Canada’s agri-food system</b>	Maximize yield, production, and exports (and thus maximize input use)	Retain yield, production, and export focus but attenuate slightly to shave a few percent off emissions, temporarily	Refocus on minimizing inputs and emissions, maintaining adequate yields, maximizing farmers’ margins, and rebalancing market power
<b>Downstream uses of farm products</b>	Nutritious food alongside junk food and excess calories, food waste, biofuels, and too much grain used to feed livestock	Rethink food waste, denutritionalization, etc. and improve system performance by a few percent	A new focus on maximizing healthfulness and safety of food and on <i>feeding people</i>
<b>Fertilizer use</b>	Fertilizer is used in ever-larger quantities to produce ever-higher farm product output tonnage	Efficiency curbs use slightly, but the trend to use more and more overwhelms small initial reductions, and tonnage and emissions resume increasing	Synthetic fertilizer comes to be seen as a precious resource and is used sparingly; alternatives are maximized
<b>Overall farming approaches</b>	Conventional, high-input agriculture increasingly reliant on fertilizers, pesticides, and fossil fuels	Green plans and environmental strategies to moderate upward trends in chemical and fertilizer use, temporarily	Alternative approaches, drawing inspiration from low-input, agroecological, organic, regenerative, holistic, etc.

Readers can imagine further examples. Again, the table does not catalogue NFU recommendations; rather, it illustrates that different kinds of changes correspond to different levels of ambition and time scales. It also highlights the limitations and likelihood of reversals of incremental changes and efficiency measures. In their effects, tweaks to business-as-usual tend to be weak and their benefits small and soon reversed. Our multiple planetary crises (carbon, nitrogen, extinction, depletion, pollution) have reached such severity that nothing less than fundamental transformation will suffice.

That said, in the very near term we can begin with incremental changes and efficiency measures.

200 Paul Ciotti, “Freaked Out by Technology,” *Reason*, August 1, 1983, <https://reason.com/1983/08/01/freaked-out-by-technology/>; H. L. Mencken, *Prejudices, Second Series* (New York: Alfred A. Knopf, 1920), 158, <https://archive.org/details/prejudicesecon01mencgoog/page/n8/mode/2up>.

## 13. Responses: Incremental and near-term

*The large impact of synthetic N fertiliser on climate emissions requires the development of a comprehensive scheme to reduce its overall use and increase efficiency of N recycling in agricultural and food systems. ... There is no doubt that emissions from synthetic N fertilisers need to be reduced (instead of increasing as predicted under current trajectories), if the goal of keeping global heating within 1.5 °C of pre-industrial levels is to be achieved.*  
—Stefano Menegat et al. 2021.<sup>201</sup>

Canada has committed to achieve an economy-wide reduction in GHG emissions of 40 percent by 2030 and to reach net zero by 2050. Specific to farming, the federal government's December 2020 climate plan<sup>202</sup> committed to a "national emission reduction target [for 2030] of 30% below 2020 levels from fertilizers." In addition to this fertilizer-related target, the government has pledged to reduce methane emissions from livestock production as part of Canada's larger pledge to reduce overall methane emissions to 75 percent below 2012 levels by 2030.<sup>203</sup> Clearly, emissions from agriculture will have to fall as we move toward 2030.

In this chapter, we look at incremental changes and, specifically, at what policymakers might do over the next eight years to support farmers in reducing fertilizer-related emissions by 30 percent. In a later chapter we will go beyond the incremental to examine transformative changes farmers may want to embrace as Canada and the world transition toward near-zero emissions.

### We do not have to reinvent the wheel

The following section can be brief because paths to a 30 percent reduction in nitrogen-related emissions have already been detailed by Agriculture and Agri-Food Canada (AAFC)<sup>204</sup> and by Farmers for Climate Solutions (FCS).<sup>205</sup>

The following summary is adapted from AAFC and FCS. In general, fertilizer-related emissions can be cut by 30 percent or more by maximizing implementation of a combination of the following measures:

1. 4R fertilizer practices, which are:
  - a. Right time. Shifting from fall fertilizer application to spring.
  - b. Right Placement. Minimizing surface spreading in favour of subsurface banding.

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201 Menegat, Ledo, and Tirado, "Greenhouse Gas Emissions from Global Production and Use of Nitrogen Synthetic Fertilisers in Agriculture," 8.

202 Environment and Climate Change Canada, "A Healthy Environment and a Healthy Economy: Canada's Strengthened Climate Plan to Create Jobs and Support People, Communities and the Planet."

203 Environment and Climate Change Canada, "Canada to Launch Consultations on New Climate Commitments This Month, Establish Emissions Reduction Plan by the End of March 2022," news releases, December 3, 2021, <https://www.canada.ca/en/environment-climate-change/news/2021/12/canada-to-launch-consultations-on-new-climate-commitments-this-month-establish-emissions-reduction-plan-by-the-end-of-march-2022.html>.

204 Agriculture and Agri-Food Canada, "Discussion Document on Reducing Emissions from Fertilizer."

205 Farmers for Climate Solutions (FCS), "APF Task Force Summary Report: Rooted in Climate Action: An Ambitious Roadmap for Emissions Reduction and Resilience in the next Agricultural Policy Framework" (Creemore, ON: FCS, May 2022), [https://static1.squarespace.com/static/5dc5869672cac01e07a8d14d/t/62aa04be38491d26c140e562/1655309514926/FCS-APF+Summary+Report\\_June+2022\\_web.pdf](https://static1.squarespace.com/static/5dc5869672cac01e07a8d14d/t/62aa04be38491d26c140e562/1655309514926/FCS-APF+Summary+Report_June+2022_web.pdf); Farmers for Climate Solutions (FCS) and various authors, "Technical Emissions Report: Agricultural Policy Framework (APF) Recommendation" (Creemore, ON: FCS, May 2022), [https://static1.squarespace.com/static/5dc5869672cac01e07a8d14d/t/62a9d33e5b80b358fd3441e0/1655296838545/FCS+APF+Recommendation-Technical+Emissions+Report\\_June+2022.pdf](https://static1.squarespace.com/static/5dc5869672cac01e07a8d14d/t/62a9d33e5b80b358fd3441e0/1655296838545/FCS+APF+Recommendation-Technical+Emissions+Report_June+2022.pdf).



- c. Right source. Maximizing use of enhanced efficiency fertilizers (EEFs) which employ coatings<sup>206</sup> and/or nitrification and/or urease inhibitors.
- d. Right rate.
  - i. More careful “quantitative” determination of right rate, including:
    1. Annual, *independent*, soil testing with adequate spatial resolution;
    2. Taking account of all N removals and sources (including soil nitrogen mineralization, manures, commercial fertilizers, and fixation by legumes) so as to calculate N balances for each field;
    3. Attenuating rates to take account of gains from other 4R efficiency measures (such as right placement and right time);
    4. Setting rates based on actual average yields (e.g., five-year averages plus five percent), not on maximum or “target yields,” i.e., eliminating “insurance nitrogen” that in most years goes to waste into the environment. Dr. David Burton estimates that setting rates this way “could result in a 10% reduction in synthetic N fertilizer use without a statistically significant decrease in yield.”<sup>207</sup> A variation is to set rates for maximum net economic return, not for maximum yield. Farmers need to focus on margin-maximizing rates, not yield-maximizing rates, and to understand that the two will not be the same; and
    5. Measuring the amount of nitrate remaining in the soil after harvest to assess whether appropriate rates have been used and to minimize losses of N<sub>r</sub> to the environment.
  - ii. Split application. Applying a portion of fertilizer with the crop and then monitoring growing conditions and probable yield to calculate the proper amount of fertilizer to add later in the growing period.
2. Enhanced Environmental Farm Plans (EFPs) that can include Emission Reduction Plans and Nutrient Management Plans to enable farmers to better understand the sources of their emissions, to implement plans to reduce them, and to quantify progress in reducing GHGs.
3. Where feasible, cover crops that in the fall can “catch” nitrogen that might otherwise be lost into the atmosphere or hydrosphere.
4. Precision agriculture and variable-rate application technologies, especially section control, which shuts off flows to sections of a seeding implement and thereby prevents double application of fertilizer. Though these last practices come with caveats.<sup>208</sup>

Critical to all the preceding is for farmers to have ready access to independent extension agrologists—public servant, public interest agrologists who are not salespeople for input sellers and who can work with farmers to optimize, minimize, and find alternatives to purchased inputs.

206 To avoid soil contamination by micro-plastics, Canada must ban plastics in fertilizer coatings and require natural materials. See Giulia Carlini and Dana Drugmand, “Sowing a Plastic Planet: How Microplastics in Agrochemicals Are Affecting Our Soils, Our Food, and Our Future” (Washington, D.C.: Center for International Environmental Law (CIEL), May 2022), [https://www.ciel.org/wp-content/uploads/2022/05/Sowing-a-Plastic-Planet\\_final23may22.pdf](https://www.ciel.org/wp-content/uploads/2022/05/Sowing-a-Plastic-Planet_final23may22.pdf).

207 Farmers for Climate Solutions (FCS) and various authors, “Technical Emissions Report: Agricultural Policy Framework (APF) Recommendation.”

208 We must ensure that farmers are not pushed to adopt corporate-controlled Big Data platforms. See Darrin Qualman and National Farmers Union, “Tackling the Farm Crisis and the Climate Crisis: A Transformative Strategy for Canadian Farms and Food Systems” (Saskatoon: NFU, 2019), Appendix F, <https://www.nfu.ca/wp-content/uploads/2020/01/Tackling-the-Farm-Crisis-and-the-Climate-Crisis-NFU-2019.pdf>; ETC Group, “Breaking Bad: Big Ag Mega-Mergers in Play” (ETC Group, 2015), <http://www.etcgroup.org/content/breaking-bad-big-ag-mega-mergers-play>; Pat Mooney and ETC Group, “Blocking the Chain: Industrial Food Chain Concentration, Big Data Platforms and Food Sovereignty Solutions” (Berlin: ETC Group, 2018), [https://www.etcgroup.org/sites/www.etcgroup.org/files/files/blockingthechain\\_english\\_web.pdf](https://www.etcgroup.org/sites/www.etcgroup.org/files/files/blockingthechain_english_web.pdf).

**Table 7. Emissions reductions from various fertilizer beneficial management practices as quantified by FCS.**

Beneficial Management Practice	Emissions Reduction (kt CO <sub>2</sub> e/y)
<b>Manure Management</b>	<b>250</b>
BMP 1 - Conserving the N content of manure in storage	250
<b>Synthetic N Fertilizer Management</b>	<b>3,485</b>
BMP 2 - Quantitative determination of Right Rate	1,115
BMP 3 - Increased adoption of precision nitrogen management	360
BMP 4 - Increased use of enhance efficiency nitrogen fertilizer	1,860
BMP 5 - Elimination of fall N application	200
<b>Land Application of Manure Management</b>	<b>535</b>
BMP 6 - 4R management of manure	165
BMP 7 - Improved crediting of organic N sources	370
Total	<b>4,270</b>

Source: Reproduced from Farmers for Climate Solutions (FCS).<sup>209</sup>

Table 7 summarizes the emission-reduction measures considered by FCS. Their *Technical Emissions Report* notes that “the above represent a total reduction of 3.5 Mt CO<sub>2</sub>e/y in N<sub>2</sub>O emissions. When expressed [as] a percentage of the 10.6 Mt CO<sub>2</sub>e/y of the direct N<sub>2</sub>O emissions associated with N fertilizer use this represents a 33% reduction in emissions.”<sup>210</sup> FCS provides a map to reach the government’s 2030 fertilizer-emission-reduction target of 30 percent.

Just as FCS concludes that a 30 percent emissions reduction is attainable, so does AAFC. Table 8 is reproduced from the Department’s March 2022 Discussion Document on Reducing Emissions from Fertilizer.<sup>211</sup>

209 Farmers for Climate Solutions (FCS) and various authors, “Technical Emissions Report: Agricultural Policy Framework (APF) Recommendation,” 33.

210 Farmers for Climate Solutions (FCS) and various authors, “Technical Emissions Report: Agricultural Policy Framework (APF) Recommendation,” 33.

211 Agriculture and Agri-Food Canada, “Discussion Document on Reducing Emissions from Fertilizer.”

**Table 8. Emissions reductions from various fertilizer beneficial management practices as quantified by AAFC.**

	<b>BMP</b>	<b>Regional applicability</b>	<b>Current adoption level</b>	<b>Potential new area (Mha)</b>	<b>Potential emissions reduction</b>	<b>Total emission reduction based on 100% adoption (Mt CO<sub>2</sub>e /yr)</b>	<b>Confidence level</b>	<b>Feasibility of adoption</b>
<b>Rate</b>	Soil N test annual for spring fertilizer application	All regions	low	5.7	5-15%	0.23	high	medium/ high
	Accounting for N in previous legume crop	All regions	medium/ high	4.9	10-20%	0.63	medium	high
<b>Time</b>	Applying N in the spring compared to the fall	Mainly west	high	3.3	5-15%	0.12	medium	high
	Fertigation (injection of fertilizers with irrigation)	Mainly west	low	0.3	15-25%	0.02	medium	medium
	Split application/sidedress with rate adjustment based on sensors	Mainly east	medium	1.9	15-35%	0.65	high	medium
<b>Placement</b>	Apply in bands/injection accompanied by reduced rate	All regions	high-west medium-east	3.0	5-15%	0.24	high	medium/ high
<b>Source</b>	Enhanced efficiency fertilizers, inhibitors or slow release	All regions	very low	18.1	15-35%	2.35	high	medium
	Replace inorganic fertilizer with manures, compost, or digestate	All regions	low	1.4	10-20%	0.15	medium	high
<b>Conservation management</b>	Conservation tillage	All regions	high-west medium-east	1.6	5-15%	0.15	medium	high
	Improved drainage design	Mainly east	medium / high -east	0.6	10-30%	0.13	low	medium
<b>Other</b>	Increasing legumes in rotations	Mainly west	low	1.5	15-25%	0.1	medium	low/ medium

Source: Reproduced from AAFC.<sup>212</sup>

AAFC's proposed reduction measures add up to even more than FCS's: 4.77 Mt CO<sub>2</sub>e per year. AAFC's tonnage numbers, however, are based on 100 percent adoption and thus should be thought of as maximum values, not wholly attainable. Nonetheless, the quantifications by AAFC scientists show that a 30 percent reduction in emissions is attainable and point the way to achieving those reductions.

<sup>212</sup> Agriculture and Agri-Food Canada, "Discussion Document on Reducing Emissions from Fertilizer."

In addition to these on-farm measures associated with fertilizer use, measures are also needed upstream, in fertilizer production. Emissions from the production of the nearly 3 million tonnes of nitrogen-in-fertilizer that Canadian farmers use each year total about 7.5 Mt CO<sub>2</sub>e.<sup>213</sup> Several measures could reduce those production emissions, including:

- i. carbon-capture and storage at fertilizer production facilities;
- ii. switching to zero-emission energy sources such as electricity from solar photovoltaic panels and wind turbines; and
- iii. utilization of hydrogen from green, non-emitting sources rather than from natural gas.

Much more could be said about near-term incremental changes in nitrogen use beneficial management practices: about steps to maintain yields as farmers adopt various efficiency measures; about ways to maintain and increase margins and net incomes; about how governments might incentivize measures and cover additional costs such as the incremental cost of enhanced efficiency fertilizers. That discussion is already well underway, however, and will not be repeated here. Suffice it to say, the combination of savings by farmers from increased fertilizer-use efficiency coupled with targeted incentives and cost-sharing programs from governments can leave farmers better off financially even as we reduce GHG and other emissions from fertilizer use by 30 percent by 2030. Key, though, is a strong partnership with governments to help farmers deal with added costs. Alone, farmers will not succeed in reducing emissions.

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213 Qualman and National Farmers Union, "Agricultural Greenhouse Gas Emissions in Canada....2nd Ed.," Table 3.

CO<sub>2</sub> = carbon dioxide | CO<sub>2</sub>e = carbon dioxide equivalent | N<sub>2</sub>O = nitrous oxide | CH<sub>4</sub> = methane | NH<sub>3</sub> = ammonia | NO<sub>x</sub> = nitrogen oxides | Mt = million tonnes

## 14. The limits of efficiency

*The world is getting more efficient at using many natural resources—but not nitrogen. Over the past fifty years, humans have used more nitrogen in the environment, largely as fertiliser, than virtually any other element. More than half of the nitrogen applied to farmland is now polluting rivers rather than being absorbed by crops.*  
—United Nations Environmental Programme.<sup>214</sup>

*The efficiency of nutrient use is very low: considering the full chain, on average over 80% of N ... end[s] up lost to the environment, wasting the energy used to prepare [it], and causing pollution through emissions of the greenhouse gas nitrous oxide (N<sub>2</sub>O) and ammonia (NH<sub>3</sub>) to the atmosphere, plus losses of nitrate (NO<sub>3</sub><sup>-</sup>)... to water.*  
—Mark Sutton, *Our Nutrient World*.<sup>215</sup>

To nearly every resource or environmental crisis, among the first solutions proposed is efficiency. If oilwells are running dry or atmospheric carbon sinks filling up, the proffered solutions include more efficient cars and furnaces. In this chapter, we explore the many reasons why efficiency and related “best management practices” cannot provide a solution to our planetary nitrogen crisis. The current system, highly and increasingly dependent on fertilizer and other petro-industrial inputs, cannot be made “sustainable” by a tune-up. Below are some reasons why.

### Efficiency seldom reduces resource and energy use: It often increases use

Contrary to our assumptions, efficiency—because it lowers our effective cost of using a material (e.g., gasoline or nitrogen) or increases our effective benefit—often leads to *more* use of that material, not less. This is the “Jevons paradox” or “rebound effect.” And we have known about it for 150 years. Commenting in 1865 on the fact that steam engines had become ten times more fuel-efficient, but that coal use had gone up, not down, Jevons wrote that it is “wholly a confusion of ideas to suppose that the economical use of fuels is equivalent to a diminished consumption. The very contrary is the truth.”<sup>216</sup>

To give a more recent example: Since the middle of the 20<sup>th</sup> century, engineers and aircraft companies have tripled the fuel efficiency of jetliners; today, it takes one-third the fuel to move a passenger a given distance.<sup>217</sup> But fuel use has increased seventeenfold! Increased fuel-efficiency made flying much cheaper and that cost reduction contributed to a fiftyfold increase in utilization.

The preceding is not to argue against making fertilizer production and use as efficient as possible, but rather to make the point that we should not expect efficiencies *alone* to provide significant or durable reductions in tonnage. Stated another way: Most farmers would claim that they are now using fertilizer more efficiently than in past decades. If that is true, then efficiency is today at a maximum yet tonnage is also at a maximum. The data from Canadian fertilizer use provides another example of the Jevons Paradox: greater efficiency alongside higher use.

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214 United Nations Environment Programme (UNEP), “#fridayfact: More Than Half of Nitrogen Applied to Cropland Is Now Washing into Our Rivers.”

215 Sutton et al., *Our Nutrient World*, viii.

216 William Stanley Jevons, *The Coal Question* (London and Cambridge: MacMillan and Co., 1865), 103.

217 Qualman, *Civilization Critical*, 184.

## Efficiency reaches limits

Whether it be a furnace, a coal-fired power plant, a lightbulb, or a jet plane, we can increase efficiency by only so much before we encounter absolute limits. For example, though a modern LED lightbulb is 15 times more efficient than an early incandescent,<sup>218</sup> that LED bulb is nearing the absolute limit of efficiency in turning electricity into visible light: its efficiency cannot be doubled again. To give another example, the large electric motors in factories and mines turn more than 90 percent of the energy in electricity into usable shaft rotation power. Further efficiency gains will be tiny.

## Growth overwhelms and undoes efficiency

Efficiency gains face hard limits set by the laws of thermodynamics, but economic growth is not similarly limited: we are told that we can go on doubling and redoubling the size of the Canadian economy. (It grew sixteenfold in the 20<sup>th</sup> century and its continued 2.5+ percent growth rate has it on track to again increase sixteenfold in the 21<sup>st</sup>.) Thus, we may be able to squeeze a 20 or 30 percent efficiency gain out of a device, process, or energy converter, but economic growth of 100, 200, 400, 800, or 1,600 percent will dwarf and reverse any such gains. Fertilizer use has nearly doubled since 2006. We might expect tonnage to double again in coming decades: a 100 percent increase. Thus, even if we achieve a 30 percent emissions reduction via efficiency, the system's growth imperative may overwhelm our efforts.

## Efficient means do not scale up or aggregate to efficient ends

Though we may have efficient means (e.g., a Prius or Tesla) we may at the same time pursue inefficient or wasteful *ends* (e.g., driving 15 blocks to buy a package of cigarettes). To give another example, air conditioners have become very efficient. But imagine five such AC units cooling the empty and seldom-visited mansion of a jet-setting billionaire. What does it mean to call such units "efficient"? If we use efficient means to pursue ends that are trivial, unnecessary, counterproductive, or damaging, is this still "efficient"? Can we efficiently produce food that will be discarded, turned into biofuels for too-large automobiles engaged in unnecessary commuting, or overconsumed to contribute to diabetes?

## In the case of nitrogen, we are not pursuing efficiency

The preceding points are general: insights into why our common instincts are wrong regarding efficiency-leads-to-decreased-resource-use. Now we will focus specifically on nitrogen fertilizer.

When we do, we find:

1. Efficiency of nitrogen use is low;
2. In some cases, efficiency has increased slightly in recent years, but remains well below the levels of two or three generations ago;
3. Even if we use nitrogen more efficiently, if we simultaneously use much more nitrogen, then system losses and ecosystem impacts will increase, not decrease;
4. Feeding grain to livestock dramatically reduces nitrogen use efficiency, yet our plan is to feed still more grain to livestock; and
5. The most effective and durable way to increase nitrogen use efficiency is to reduce tonnage.

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218 William Nordhaus, "Do Real-Output and Real-Wage Measures Capture Reality? The History of Lighting Suggests Not." In *The Economics of New Goods* (Chicago: University of Chicago Press, 1996).

First, a definition: Nitrogen use efficiency (NUE) = the ratio of nitrogen in a chosen product output (e.g., harvested grain) to new nitrogen inputs (including synthetic fertilizer, biological N fixation, and NO<sub>x</sub> formation via combustion).<sup>219</sup> We can express that ratio as a fraction:

$$\text{Nitrogen use efficiency (NUE)} = \frac{\text{nitrogen in chosen product (e.g., grain)}}{\text{new nitrogen inputs (incl. synthetic fertilizer, biological N fixation, and NO}_x \text{ formation)}}$$

Thus, nitrogen use efficiency increases when the top number, the numerator, output, gets larger. And efficiency similarly increases when the bottom number, the denominator, the tonnage of inputs into the system, gets *smaller*. Not surprising: Since the middle of the 20<sup>th</sup> century, as nitrogen inputs into Canadian and other agricultural systems have gone up, NUE has gone down. As we have pushed more and more N into the system, efficiency has declined. It may have rebounded slightly in recent decades,<sup>220</sup> but it remains well below the levels of the 1960s, '70s, and '80s.<sup>221</sup>

Sutton et al. tell us that:

One of the central problems to be faced is that increasing nutrient inputs to agriculture tends to greatly reduce nutrient use efficiency (NUE). ... While the green revolution has helped feed humans, it has thus substantially reduced NUE in much of the world, while greatly increasing pollution of the environment.<sup>222</sup>

Looking at the global system in the 2000 – 2010 period, Sutton et al. point out that:

Of 180 [Mt] N input through a combination of manufactured fertilizers and biological nitrogen fixation annually, only 28 [Mt] is available in food [for] human consumption (i.e. 16%), with only 19 [Mt] (i.e. 11%) actually consumed, given levels of food waste prior to consumption. *These startling estimates emphasize the inefficiency of the global system* [italics added].<sup>223</sup>

Sutton's numbers are worth restating because they so effectively illuminate the inefficiency of our nitrogen use: Humans add about 180 million tonnes of reactive nitrogen annually to global food systems, and a combination of losses in fields and losses in animal feeding chains means that this is turned into just 28 million tonnes of nitrogen in food supplies. Of that, as a result of food waste, only 19 million tonnes is actually consumed by humans. Globally, NUE<sub>system</sub> = 11 percent.

NUE in the cropping system (NUE<sub>crop</sub>) is higher: about 50 percent in Canada.<sup>224</sup> NUE falls dramatically as crops are fed to livestock and those animals turn 5 to 10 units of N in feedgrain into 1 unit of N in meat or dairy products (see Ch. 6). Sutton notes that the more grain we feed to livestock, the more NUE<sub>system</sub> declines: "By increasing the fraction of livestock in the food chain, overall nutrient use efficiency has decreased substantially, leading to a further increase in pollution losses...."<sup>225</sup> He reiterates that "only 6% of the N<sub>r</sub> consumed by livestock globally reaches human food (prior to food waste) ... emphasizing the critical role of livestock in the low overall values NUE<sub>N</sub> along the agri-food chain."<sup>226</sup> (Again, please

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219 Sutton et al., *Our Nutrient World*, 58.

220 Karimi et al., "An Updated Nitrogen Budget for Canadian Agroecosystems."

221 Zhang et al., "Quantification of Global and National Nitrogen Budgets for Crop Production," 530.

222 Sutton et al., *Our Nutrient World*, 12.

223 Sutton et al., *Our Nutrient World*, 20.

224 Karimi et al., "An Updated Nitrogen Budget for Canadian Agroecosystems."

225 Sutton et al., *Our Nutrient World*, 12.

226 Sutton et al., *Our Nutrient World*, 21.



note that such appraisals apply primarily to grain-based animal feeding systems and not to grazing systems. The latter can proceed largely without synthetic fertilizers and can be very important in protecting biodiverse grassland ecosystems.)

In Chapter 8, this report details the nitrogen cascade and the losses of ammonia, nitrate, nitrogen oxides, and nitrous oxide to the atmosphere, waters, and ecosystems, as well as the human health impacts of those losses. Critical to understand is this: Even if we significantly increase NUE, if at the same time we increase N tonnage, losses to the environment and damage to ecosystems and human health will go up, not down. Greater NUE  $\neq$  lower losses if the inputs to the system are increasing. Focusing on Canada, Karimi et al. underscore this point:

Despite intensive research and impressive advances in technologies, including precision farming, no-till farming, new fertilizer formulations, remote sensing, improved diet formulation for livestock, and sophisticated diagnostic techniques, the apparent N use efficiency [NUE] has only marginally increased. Indeed, *the absolute mass of N apparently lost to the environment has actually increased because of increasing inputs to agroecosystems* [italics added].<sup>227</sup>

Karimi et al. calculate that Canada's  $NUE_{crop}$  rose from 46.7 percent in 1996 to 50.8 percent in 2016, but the authors note that: "Although N use efficiencies at the crop, livestock and agroecosystem scales have improved marginally over the last two decades, a rise in the total mass of N added to Canadian agricultural lands is such that the total mass of N potentially lost to the environment *has increased by over 50%*" [italics added]. Slightly increased efficiency but dramatically increased tonnage means higher, not lower, losses to the environment and increased, not decreased, damage to climate, ozone, groundwater, freshwaters, oceans, biodiversity, and human health.

The evidence is clear: Large increases in damaging emissions have occurred despite efficiency gains. Efficiency measures alone do not reduce emissions and adverse impacts. Absolute reductions in rates and tonnage are needed. For those who react with hostility to such ideas, recall that humans have tripled the amount of N moving through terrestrial ecosystems and that in N use we have far exceeded the safe operating limits for the planet. Techno-tweaks, bolt-on solutions, incremental changes, and efficiency measures will not be sufficient. Transformative change and a return to safe operating limits are the only adequate responses.

## Efficiency, conclusion

Efficiency is critically important—something we must pursue and maximize. It brings benefits, such as decreased costs. Efficiency is important *but not sufficient*. Efficiency alone is not enough to create a significant and durable decline in demand for goods, services, materials, energy, or, in this case, fertilizer. Without doubt, we need efficient means, yes, but even more crucially, we need those efficient means coupled to carefully chosen and limited ends. We must practice intelligent restraint.

This chapter has looked critically at efficiency in order to show that small changes, BMP adoption, technological innovations, and incremental adjustments will not be enough to deal adequately with the nitrogen crisis we have unleashed. Transformative system change is needed, and that is the topic of the next and final chapter.

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227 Karimi et al., "An Updated Nitrogen Budget for Canadian Agroecosystems," 13.

## 15. Responses: The need for transformation

*Feeding a future population of [approximately] 10 billion people while remaining within the safe operating space for N is only possible through drastic changes to both food production systems and consumption patterns.*

—Lena Schulte-Uebbing et al., “From Planetary to Regional Nitrogen Boundaries.”<sup>228</sup>

*Of the nine [planetary boundaries (PBs)], five are in the high risk or increasing risk zones, with agriculture the major driver of four of them and a significant driver of the remaining one.... There are numerous possible intervention points to reduce the impact of agriculture on PBs.... However, nothing less than a radically transformed system will be required, with numerous changes made to all aspects of production ... and with changes made to all aspects of the broader food system... [emphasis added].*

—Bruce Campbell et al., “Agricultural Production as a Major Driver of the Earth System Exceeding Planetary Boundaries.”<sup>229</sup>

*The adoption of agriculture-management practices based on ecological principles must be an integral component of any solution to the environmental problems of the modern era.*

—H. Henry Janzen et al. and AAFC, “Better Farming, Better Air.”<sup>230</sup>

This report has conveyed a lot of bad news. It has provided extensive evidence that we are in a crisis—that our global tripling of nitrogen flows is killing millions of people and damaging nearly every one of our planet’s ecosystems. Such news creates anxiety and tension. It creates the expectation that this final chapter will provide “solutions”: that it will relieve that anxiety and dispel that tension and allow readers to leave with the feeling that, though the problem may not be solved, there is at least a clear path toward a solution.

There is not; the path is not clear—in either sense: clearly defined or without obstructions. And the path to real transformation certainly cannot be described in a few pages. Humanity is in an excruciating predicament. We have created immensely powerful systems that gravely imperil ourselves and our children. The power of these systems leads to two main outcomes: helping create a modern world that includes pharmaceuticals, air travel, the internet, large cities, etc.; and *ruthlessly magnifying humanity’s errors*. Like Shiva, human systems have become powerful creators and destroyers. Haber-Bosch nitrogen fertilizer embodies that duality.

Regrettably, this chapter will not let readers go away feeling that anyone possesses a plan to “solve the problem.” No one has such a plan. To problems of this magnitude, there are no solutions, only responses. The path ahead can be mapped only as we go, so we must set out. We must actually commit ourselves to moving forward, into an uncertain future, but in a direction that actually moves us toward an improved situation—toward lower environmental impacts and *true* sustainability. Currently, we are moving in the opposite direction. So if a path to a better future exists it lies behind us, in that we are facing away from it and moving away from it. We must turn around.

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228 Lena Schulte-Uebbing et al., “From Planetary to Regional Nitrogen Boundaries for Targeted Policy Support,” *Research Square* Pre-print (2022), <https://www.researchsquare.com/article/rs-149125/v1>.

229 Bruce Campbell et al., “Agriculture Production as a Major Driver of the Earth System Exceeding Planetary Boundaries,” *Ecology and Society* 22, no. 4 (2017): 14.

230 H.H. Janzen et al., “Better Farming, Better Air: A Scientific Analysis of Farming Practice and Greenhouse Gases in Canada” (Ottawa: AAFC, 2008), iv, [http://publications.gc.ca/collections/collection\\_2009/agr/A52-83-2008E.pdf](http://publications.gc.ca/collections/collection_2009/agr/A52-83-2008E.pdf).

The preceding said, several things are clear:

1. Small changes to business-as-usual will not be enough; efficiency will not fix this; there is no clever techno-solution just around the corner. Our efficiency levels and technological achievements are at historic highs, yet so too are the scale and menace of our problems. We must abandon the facile, evidence-defying idea that adding technologies reduces problems.
2. Transformative, foundational systemic change is needed. We have an agricultural system that maximizes exports, output, inputs, and emissions but also losses and dissipation; one that is massively and increasingly dependent on fossil-fuel-derived nitrogen and other petro-industrial inputs; one that maximizes corporate profits even as it continuously pushes farmers off the land; and we need a wholly different kind of agricultural system.
3. Models exist that can begin to show a way out: low-input; organic; regenerative; agro-ecological; and minimum-input no-till (MINT)<sup>231</sup> productions systems are where we should begin our search for alternatives. Moreover, we must remember this reassuring fact: for 99 percent of the time that humans have practiced agriculture—for 9,900 of the past 10,000 years—our farming systems were zero-input, zero-emission, and solar-powered. They did not spew massive quantities of emissions that damaged the climate, ozone layer, or oceans. Those farming systems did have limitations, no doubt! A “return to the past” is not the way forward. Neolithic farming systems cannot feed 8 billion urbanized humans and our too-large collection of livestock. Nonetheless, keeping in mind that for 99 percent of history we proceeded differently enables us to sidestep the mind-trap that “there is no alternative” or that fundamental change is impossible. *Not* changing is impossible, because continuing down our business-as-usual path of doubling and redoubling will lead to Earth systems hostile and destructive to the project of human civilization.
4. As the 21<sup>st</sup> century unfolds, farmers need to get less from industry and more from biology. We need to reconnect with biological processes and the circular flows of nature as ways of replacing some of the fertility farmers currently purchase. In the 20<sup>th</sup> century, human systems, including agriculture, broke free (dis-integrated) from natural cycles and systems. **In the 21<sup>st</sup> century, a re-integration must occur. This re-integration with Earth’s processes, cycles, flows, and limits is our North Star in navigating the project of transformative change. Though the path is not yet mapped, it is in this direction that we must set out.**
5. Farmers need to be supported as we chart a new course. Farmers have spent much of the past two generations in an income crisis (1985 – 2008), and now face a climate crisis. Many lost most of their grain crops and livestock forage to drought in 2021. Since 2010, debt has doubled. Though in some years gross and net returns can be very large, the production and financial risks farmers face can be grave. Their costs are huge. Farmers alone cannot shoulder new costs that cut deep into volatile and oft-tight margins. Governments must help farmers shoulder the risks within our food system and share the costs as farmers invest in new systems to reduce emissions and transform production systems. Cost-sharing, support programs, incentives, and supportive policies are essential.
6. Governments must broaden their focus beyond export maximization and instead embrace multiple goals that include maximizing farmers’ margins and net incomes and *increasing the number of farmers*. The transformations we face will be difficult for all Canadians, and even more so for farmers. But if farmers come together and if governments can regain their integrity and their democratic focus as servants of the people, and if we and our governments can move from short-term to long-term thinking in time to save ourselves, then we can deploy collective responses that can help farmers and all Canadians map and travel the path ahead.

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231 Qualman and National Farmers Union, “Tackling the Farm Crisis and the Climate Crisis,” 47–48.

7. We need *institutional* change: new goals and priorities at all levels of government, new institutions such as a Canadian Farm Resilience Agency (CFRA),<sup>232</sup> and a mass deployment of independent, public servant extension agrologists who are not connected to input sellers and who can advise farmers on fertilizer optimization and input reduction. A CFRA could also provide independent soil testing and advice on climate adaptation and operate demonstration farms where resilient, low-emission farming practices could be refined and showcased.
8. We must not get lured down false paths. In the face of intensifying, converging planetary crises, corporations and aligned entities are advancing self-serving false solutions: emissions offset trading, biofuels, techno-salvationist Big Data schemes, driverless tractors, etc. These are false solutions—paths that lead us in a circle, or to a dead end, or off a cliff. Farmers, all citizens, and our elected officials must think and analyze as hard as we can and maintain a healthy skepticism to avoid being lured toward seductive but ultimately damaging false solutions.

The preceding eight points fall short of charting a path, but they do describe much of the terrain we must traverse. And, most important, they identify the destination toward which we must navigate.

Rather than telling ourselves and each other that we have a plan, that we are moving toward sustainability, or that efficiency and technology and best-management practices will solve this, we must instead take up our roles as responsible, engaged democratic citizens and shoulder the very real worry that this is in no way solved. We must embrace the tension and the anxiety. We must maintain this as an open question and an unsolved and pressing problem—one in urgent need of attention. We must stew on our predicament. We must maintain the tension, because that tension can give urgency and energy to the project of transformational change.

We have work to do. And no one can do it but us.

We conclude with an excerpt from the NFU's 2019 report *Tackling the Farm Crisis and the Climate Crisis*:

For hundreds of thousands of years, there was no agriculture. Then, there was a civilizational transformation. Agriculture emerged. And for about a hundred centuries, there was agriculture that was solar powered, low-input, and net-zero emission. Then, a century ago, there was another civilizational transformation—to the fossil-fuelled agricultural and industrial systems we see around us today. We are now amid yet another civilizational transformation (forced upon us by the build-up of greenhouse gases in our atmosphere and our encounters with other planetary limits)—a transition away from fossil-fuelled systems, and toward wholly new ways of organizing and energizing human food, manufacturing, transportation, and economic systems. The thousands of farm family members that make up the NFU ask that governments stretch themselves to the very limits of their capacities and help marshal all the wisdom that can be accessed within this nation of Canada so that we may navigate this transformation and emerge from it healthier, happier, more secure, and in greater harmony with the Earth systems upon which all human life and commerce depend. This report is our initial contribution toward navigating this civilizational transformation.<sup>233</sup>

**Thank you**  
**National Farmers Union**  
**August 2022**

232 Qualman and National Farmers Union, "Tackling the Farm Crisis and the Climate Crisis," 66.

233 Qualman and National Farmers Union, "Tackling the Farm Crisis and the Climate Crisis," 76.

## Glossary

**Ammonia (NH<sub>3</sub>):** A form of fixed or reactive nitrogen; the initial form of all manufactured nitrogen fertilizers; a gaseous emission product from fields that have received manure or synthetic fertilizer; a primary means by which N escapes into the atmosphere; a contributor to the creation of particulate matter, smog, and human mortality.

**Biological nitrogen fixation:** Transformation of unreactive atmospheric N<sub>2</sub> gas into fixed or reactive forms via specialized bacteria or algae, such as the symbiotic bacteria in the root nodules of legumes.

**Carbon dioxide equivalent (CO<sub>2</sub>e):** A measure that equates all GHGs to CO<sub>2</sub> using their Global Warming Potential (GWP) (see below); a “common currency” that enables various GHGs to be summed and expressed as a single value.

**Cultivation-induced biological nitrogen fixation:** Biological nitrogen fixation in human-cultivated crops such as soybeans or peas.

**Global Warming Potential (GWP):** A number that expresses the warming impact of a GHG relative to the same mass of CO<sub>2</sub> (e.g., methane, CH<sub>4</sub>, has a GWP of 28: a kg of CH<sub>4</sub> released will warm the climate 28x more than a kg of CO<sub>2</sub>).

**Leaching:** Loss of soluble N<sub>r</sub> (usually nitrate, NO<sub>3</sub><sup>-</sup>) into groundwater.

**Methane (CH<sub>4</sub>):** A greenhouse gas approximately 30 times more powerful than CO<sub>2</sub> and also the main constituent of natural gas. On farms, methane comes mainly from cattle digestion and from manure.

**Nitrate (NO<sub>3</sub><sup>-</sup>):** A form of fixed/reactive nitrogen. Soluble, it is a primary means whereby N<sub>r</sub> is leached into groundwater.

**Nitrogen (N):** An element/atom—number seven on the periodic table, between carbon and oxygen; an essential part of DNA, RNA, all amino acids, and chlorophyll; one of the core biogeochemical *cycles* on Earth.

**Nitrogen fixation:** The transformation of abundant (but biologically inactive) atmospheric nitrogen (N<sub>2</sub>) into reactive or fixed forms such as ammonia (NH<sub>3</sub>), nitrate (NO<sub>3</sub><sup>-</sup>), nitrous oxide (N<sub>2</sub>O), and nitrogen oxides (NO, NO<sub>2</sub>, NO<sub>x</sub>). The main mechanisms are biological nitrogen fixation (legumes, etc.), fertilizer production, lightning, and combustion.

**Nitrogen oxides (NO, NO<sub>2</sub>, NO<sub>x</sub>):** Reactive nitrogen compounds that are not GHGs but that contribute to air pollution.

**Nitrogen use efficiency (NUE):** The ratio of nitrogen inputs into a system relative to the nitrogen outputs. For example, if you apply 50 kgs of actual N nutrient to a hectare of wheat then harvest a crop that contains 25kgs of N (most N is contained in proteins), then your NUE = 50 percent.

**Nitrous oxide (N<sub>2</sub>O):** A GHG approximately 300 times more powerful than CO<sub>2</sub> in trapping heat. On farms, nitrous oxide comes mainly from manure decomposition and from soils, especially after application of synthetic nitrogen fertilizer or manure.

**Reactive nitrogen (N<sub>r</sub>):** All forms of fixed or biologically active nitrogen (e.g., ammonia, nitrate, nitrous oxide, and nitrogen oxides) and excluding atmospheric N<sub>2</sub>, gas which is biologically inactive.

**Volatilization:** Loss of N<sub>r</sub> into the atmosphere, primarily in the forms of ammonia, nitrous oxide, and nitrogen oxides.