How a century of ammonia synthesis changed the world

On 13 October 1908, Fritz Haber filed his patent on the "synthesis of ammonia from its elements" for which he was later awarded the 1918 Nobel Prize in Chemistry. A hundred years on we live in a world transformed by and highly dependent upon Haber–Bosch nitrogen.

GERT VAN DUINEN

Agricultural production for food and fuel has increased in the past few years; for example, oilseed rape as shown here.

Although over 78% of the atmosphere is composed of nitrogen, it exists in its chemically and biologically unusable gaseous form. Haber discovered how ammonia, a chemically reactive, highly usable form of nitrogen, could be synthesized by reacting atmospheric dinitrogen with hydrogen in the presence of iron at high pressures and temperatures. Today, this reaction is known as the Haber–Bosch process: Fritz Haber was the inventor who created the breakthrough and laid the foundations for high-pressure chemical engineering, but it was Carl Bosch who subsequently developed it on an industrial scale, for which he was awarded a Nobel Prize in 1931. The importance of Haber's discovery cannot be overestimated — as a result, millions of people have died in armed conflicts over the past 100 years, but, at the same time, billions of people have been fed.

In his Nobel lecture, Haber explained that his main motivation for synthesizing ammonia from its elements was the growing demand for food, and the concomitant need to replace the nitrogen lost from fields owing to the harvesting of crops: "it was clear that the demand for fixed nitrogen, which at the beginning of this century could be satisfied with a few hundred thousand tons a year, must increase to millions of tons"[1]. We now know that his vision was right: the current worldwide use of fertilizer nitrogen is about 100 Tg N per year.

Haber's other motivation, not mentioned in his lecture, was to provide the raw material for explosives to be used in weapons, which requires large amounts of reactive nitrogen. Haber's discovery has therefore had a major influence on both World Wars and all subsequent conflicts. In addition, the large-scale production of ammonia has facilitated the industrial manufacture of a large number of chemical compounds and many synthetic products. Thus the Haber–Bosch process, with its impacts on agriculture, industry and the course of modern history, has literally changed the world.

What Fritz Haber could not foresee, however, was the cascade of environmental changes, including the increase in water and air pollution, the perturbation of greenhouse-gas levels and the loss of biodiversity that was to result from the colossal increase in ammonia production and use that was to ensue[3]. Here we reflect on the influence that Haber's invention has had on society over the last century, both the benefits and unintended consequences. And, based on different scenarios of future nitrogen fertilizer use, we discuss some of the challenges likely to be faced by our 'nitrogen economy' in the next 100 years.

ECONOMIC AND SECURITY BENEFITS

Up until the first decades of the twentieth century, many industrial processes were dependent on limited natural reservoirs of reactive nitrogen, particularly Peruvian guano, Chilean saltpeter and sal ammoniac extracted from coal. Early attempts to fix nitrogen from the atmosphere were inefficient and energetically expensive. The Haber–Bosch process has significantly lower energy requirements and was therefore substantially cheaper, allowing it to form the basis of an alternative expanding supply of reactive nitrogen. Haber's nitrogen has since boosted the production of many previously expensive or rare compounds, such as dyes and artificial fibres, but it has had its greatest impact on the production of explosives and fertilizers[2].

EXPLOSIVES

The central role that nitrogen has in the manufacture of explosives is reflected not only in the Nobel prizes awarded to Haber and Bosch, but in the very origin of the Nobel Prize itself. Alfred Nobel's wealth was built on the development of safe methods for using nitroglycerine, and his patents for dynamite and gelignite eventually financed the Nobel Foundation. As a German patriot, Haber was keen to develop explosives and other chemical weapons, which to his mind were more humane, because they "would shorten the war"[4]. The need to improve munitions supplies was in reality a central motivation for industrial ammonia production.

With the blockade of Chilean saltpeter supplies during the First World War, the Haber–Bosch process provided Germany with a home supply of ammonia. This was oxidized to nitric acid and used to produce ammonium nitrate, nitroglycerine, TNT (trinitrotoluene) and other nitrogen-containing explosives. Haber's discovery therefore fuelled the First World War, and, ironically, prevented what might have been a swift victory for the Allied Forces. Since then, reactive nitrogen produced by the Haber–Bosch process has become the central foundation of the world's ammunition supplies. As such, its use can be directly linked to 100–150 million deaths in armed conflicts throughout the twentieth century[5].

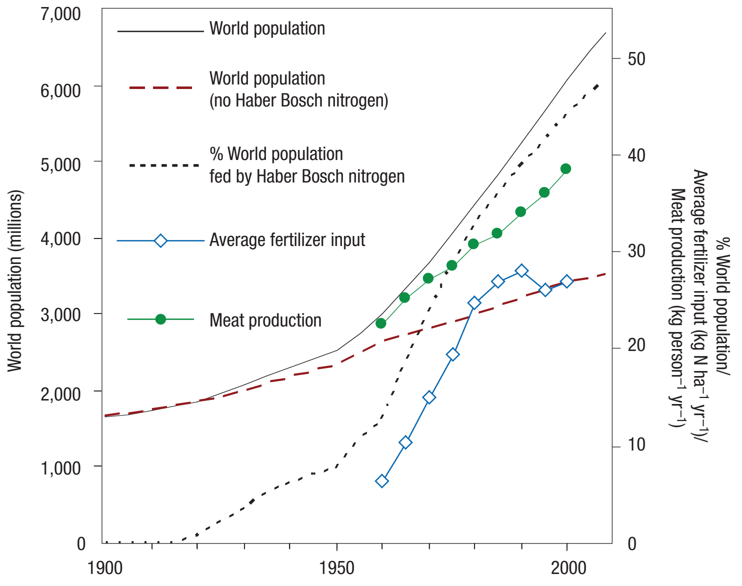

Figure 1 Trends in human population and nitrogen use throughout the twentieth century. Of the total world population (solid line), an estimate is made of the number of people that could be sustained without reactive nitrogen from the Haber–Bosch process (long dashed line), also expressed as a percentage of the global population (short dashed line). The recorded increase in average fertilizer use per hectare of agricultural land (blue symbols) and the increase in per capita meat production (green symbols) is also shown.

FERTILIZERS

At the same time, the Haber–Bosch process has facilitated the production of agricultural fertilizers on an industrial scale, dramatically increasing global agricultural productivity in most regions of the world[7] (Fig. 1). We estimate that the number of humans supported per hectare of arable land has increased from 1.9 to 4.3 persons between 1908 and 2008. This increase was mainly possible because of Haber–Bosch nitrogen.

Smil estimated that at the end of the twentieth century, about 40% of the world's population depended on fertilizer inputs to produce food[2,6]. It is difficult to quantify this number precisely because of changes in cropping methods, mechanization, plant breeding and genetic modification, and so on. However, an independent analysis, based on long-term experiments and national statistics, concluded that about 30–50% of the crop yield increase was due to nitrogen application through mineral fertilizer[7].

It is important to note that these estimates are based on global averages, which hide major regional differences. In Europe and North America, increases in agricultural productivity have been matched by luxury levels of nitrogen consumption owing to an increase in the consumption of meat and dairy products, which require more fertilizer nitrogen to produce — this is partly reflected in the global increase in per capita meat consumption (Fig. 1). In contrast, the latest Food and Agriculture Organization report shows that approximately 850 million people remain undernourished[8].

Overall, we suggest that nitrogen fertilizer has supported approximately 27% of the world's population over the past century, equivalent to around 4 billion people born (or 42% of the estimated total births) since 1908 (Fig. 1). For these calculations, we assumed that, in the absence of additional nitrogen, other improvements would have accounted for a 20% increase in productivity between 1950 and 2000. Consistent with Smil[6], we estimate, that by 2000, nitrogen fertilizers were responsible for feeding 44% of the world's population. Our updated estimate for 2008 is 48% — so the lives of around half of humanity are made possible by Haber–Bosch nitrogen.

In addition, fertilizer is required for bioenergy and biofuel production. Currently, bioenergy contributes 10% of the global energy requirement, whereas biofuels contribute 1.5%. These energy sources do not therefore have a large influence on global fertilizer use[9]. However, with biofuel production set to increase, the influence of Haber–Bosch nitrogen will only grow.

Together with the role of reactive nitrogen in ammunition supplies, these figures provide an illustration of the huge importance of industrial ammonia production for society, although, on balance, it remains questionable to what extent the consequences can be considered as beneficial.

UNINTENDED CONSEQUENCES

Of the total nitrogen manufactured by the Haber–Bosch process, approximately 80% is used in the production of agricultural fertilizers[10]. However, a large proportion of this nitrogen is lost to the environment: in 2005, approximately 100 Tg N from the Haber–Bosch process was used in global agriculture, whereas only 17 Tg N was consumed by humans in crop, dairy and meat products[11]. Even recognizing the other non-food benefits of livestock (for example, transport, hides, wool and so on), this highlights an extremely low nitrogen-use efficiency in agriculture (the amount of nitrogen retrieved in food produced per unit of nitrogen applied). In fact, the global nitrogen-use efficiency of cereals decreased from ~80% in 1960 to ~30% in 2000[12,13]. The smaller fraction of Haber–Bosch nitrogen used in the manufacture of other chemical compounds (~20%) has

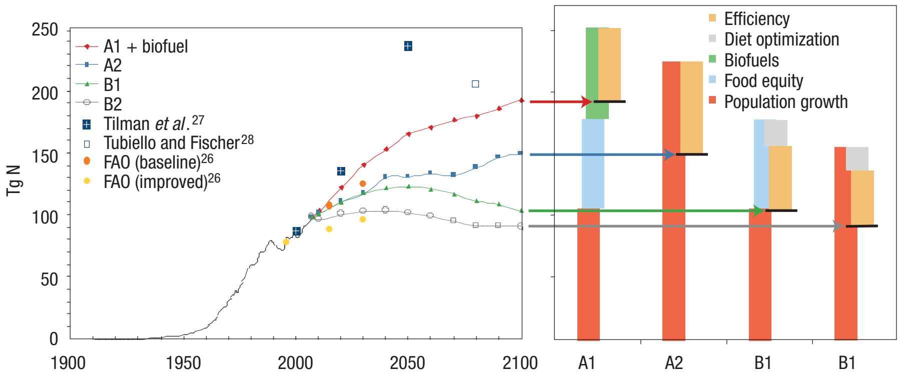

Figure 2 Global nitrogen fertilizer consumption scenarios (left) and the impact of individual drivers on 2100 consumption (right). This resulting consumption is always the sum (denoted at the end points of the respective arrows) of elements increasing as well as decreasing nitrogen consumption. Other relevant estimates[26,27,28] are presented for comparison. The A1, B1, A2 and B2 scenarios draw from the assumptions of the IPCC emission scenario[23] storylines as explained in the text.

an uncertain fate, with its escape into the environment depending on the life-cycle of the product.

A recent study suggested that approximately 40% of fertilizer nitrogen lost to the environment is denitrified back to unreactive atmospheric dinitrogen[14]. In principle this loss is environmentally benign, although it represents a waste of the energy used in the Haber–Bosch process equivalent to at least 32 MJ kg^{-1} N fixed, or about 1% of the global primary energy supply. However, the rest of the excess nitrogen escapes into environmental reservoirs, where it cascades through atmospheric, terrestrial, aquatic and marine pools before eventually being denitrified or stored as fossil reactive nitrogen. In principle, one molecule of reactive nitrogen can have multiple effects during its lifetime in the cascade. Understanding this cascade is therefore essential for the development of effective abatement measures[15].

The influence of Haber–Bosch nitrogen on the global nitrogen cycle can be seen in present-day atmospheric and aquatic nitrogen pools. Emissions of NO and NH_3 to the atmosphere have increased about fivefold since pre-industrial times[14]. Atmospheric nitrogen deposition in the absence of human influence is ~0.5 kg N ha^{-1} yr^{-1} or less, but in large regions of the world, average atmospheric deposition rates exceed 10 kg N ha^{-1} yr^{-1}, exceeding natural rates by more than an order of magnitude. Much of this reactive nitrogen is deposited in nitrogen-limited ecosystems, leading to unintentional fertilization and loss of terrestrial biodiversity. Similarly, the transfer of reactive nitrogen from terrestrial to coastal systems has doubled since pre-industrial times[16]. As with terrestrial ecosystems, many of the coastal ecosystems receiving increased nitrogen loadings are nitrogen-limited, leading to algal blooms and a decline in the quality of surface and ground waters.

In addition to these ecosystem-level disturbances, reactive nitrogen alters the balance of greenhouse gases, enhances tropospheric ozone, decreases stratospheric ozone, increases soil acidification and stimulates the formation of secondary particulate matter in the atmosphere, all of which have negative effects on people and the environment.

The effects of reactive nitrogen on the environment can be mitigated through several intervention strategies, which should focus on reducing the creation of reactive nitrogen, increasing the efficiency with which it is used, or converting it back to atmospheric dinitrogen. Such strategies could include increasing the efficiency of nitrogen use in food production, altering human diets and improving the treatment of human and animal waste[10].

Another unintended, but positive, environmental consequence of the Haber–Bosch process may be an increase in the amount of carbon sequestrated in non-agricultural ecosystems, due to an increase in atmospheric nitrogen deposition. Recent debate has focused on the response of forests[17–20], where the strength of this fertilization effect is contentious. Estimates of the amount of additional carbon stored per kilogram of nitrogen deposited range from 40 to 400 kilograms of carbon, although the most recent estimates suggest that the largest values are unlikely[18–20]. In the meantime, further efforts are being directed to understand the overall effect of reactive nitrogen on the greenhouse gas balance, including its interactions with nitrous oxide, methane, ozone and aerosols[21,22].

THE NEXT CENTURY OF HABER–BOSCH

We project global nitrogen fertilizer demand over the next century on the basis of the four storylines developed for the Intergovernmental Panel on Climate Change Special Report on Emission Scenarios (SRES)[23]. The storylines reflect varying economic, demographic and technological developments. The A1 storyline assumes a world of very rapid economic growth, a global population that peaks mid-century, and rapid introduction of new and more efficient technologies. B1 describes a convergent world, with the same global population as A1, but with more rapid changes in economic structures towards a service and information economy. B2 describes a world with intermediate population and economic growth, emphasizing local solutions to economic, social and environmental sustainability. A2 describes a very heterogeneous world with high population growth, slow economic development and slow technological change. We consider the following five parameters to be the main drivers of the estimated trends in fertilizer use, and we apply a subset of these parameters to the respective scenarios (see Fig. 2).

(1) Population growth is the main driver behind the increase in nitrogen fertilizer use. The SRES population projections range between 7 (B1) and 15 billion people (A2) in 2100. Recent research suggests that global fertility rates will continue to decrease. As a consequence, population growth is expected to eventually halt[24,25].

(2) The potential for increasing yield per hectare is large, and could allow food output to keep pace with population increases, without requiring an increase in cropping area. At the same time, an increase in fertilizer efficiency is expected. In agreement with Smil[2], we assume that nitrogen management can be improved, resulting in a 50% increase in nitrogen-use efficiency, thus reducing nitrogen application.

3) Further demand on agriculture may be posed by biofuel production, calling for an expansion of crop land as well as an increase in nitrogen demand. In the technology-oriented ‘global’ scenario (A1), we use the Organisation for Economic Co-operation and Development estimate of the maximum potential land available for bioenergy (0.74 Gha), which represents an extension equal to half the current cropland area[9].

(4) Large parts of the world population are deprived of valuable animal protein. We assume that food equity will increase worldwide meat consumption to the level observed in developed countries. Increased meat production will increase nitrogen usage because of the additional nitrogen required to produce animal feed, and the inefficiency of nitrogen use in meat-based diets relative to plant- based diets.

(5) We assume that human diets will be optimized to improve nitrogen-conversion efficiency in the production cycle. Specifically, we assume that the ratio of meat protein to milk protein (currently about 2:1) will be reversed (1:2), as the nitrogen-to-protein conversion ratio is higher in milk than meat.

Our projections are well within the low estimates provided by the Food and Agriculture Organization[26], and some higher estimates in scientific literature[27,28], which suggest a two- to threefold increase in nitrogen fertilizer use by the second half of the twenty-first century, assuming continuation of past practices. In all our scenarios, anticipated improvement in efficiency will compensate for much of the increase in fertilizer demand. Furthermore, we do not expect global protein supply to improve towards ‘food equity’ in the scenarios predicting high population growth (A2 and B2 projections). Thus the drivers towards high nitrogen use will not occur simultaneously, leading to smaller differences in annual nitrogen demand (100–150 Tg N) than would be expected from population projection alone. Only when bioenergy calls for a large increase in crop production is fertilizer nitrogen demand expected to double to nearly 200 Tg N per year. Despite the uncertainty and the many important drivers not included, all scenarios point towards an increase in future production of reactive nitrogen. This will further increase the nitrogen pressures on the environment, with uneven distribution only exacerbating the problem regionally.

THE FUTURE NITROGEN ECONOMY

It is appropriate to mark a century of Haber’s invention. Given its multiple roles in military security, food production, biofuels and a host of adverse environmental impacts, we argue that today’s society can be considered dependent on a nitrogen-based economy. It is important to note, however, that the benefits of Haber–Bosch nitrogen are not available to all people of the world, owing to financial, geographical and political constraints. It is therefore essential to provide the infrastructure to supply nitrogen where it is needed, and to use it in a sustainable way.

Fritz Haber aimed to influence the course of history by providing strategic advantages for his country in terms of food and military security. His invention for synthesizing ammonia exceeded expectations, substantially altering the course of the planet throughout the twentieth century. But, as illustrated in our future scenarios, there is a high probability that the unintended environmental consequences will not be reduced over the coming decades. Each of the main human drivers, such as growth in the population, improvement of the world’s food supply and the use of biomass to provide energy, will lead to further increases in the demand for nitrogen, and will more than compensate for expected improvements in efficiency. In the worst-case scenario, we will move towards a nitrogen-saturated planet, with polluted air, reduced biodiversity, increased human health risks and an even more perturbed greenhouse-gas balance.

Food and military security were the key objectives for Haber. For us, global environmental sustainability must surely be the main driver for future innovation. Examples of key advances to aim for include improving nitrogen-use efficiency and reducing dependency on nitrogen-intensive biofuels, as well as developing a comprehensive supply of protein and amino acids with greatly improved efficiency compared with traditional agricultural systems.

It will be interesting to look back a century from now: will another patent have changed the world to the same extent as the one Fritz Haber filed a hundred years ago?

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Acknowledgements

We acknowledge financing from the European Commission for the NitroEurope Integrated Project, the European Science Foundation for the NinE programme and the COST programme (European Cooperation in the field of Scientific and Technical Research) for COST 729. This article was prepared as a contribution to the International Nitrogen Initiative and the Task Force on Reactive Nitrogen of the United Nations Economic Commission for Europe.

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