Transforming the World

What has been the most important technical invention of the twentieth century? Airplanes, nuclear energy, space flight, television, and computers are the most common answers. Yet none of these inventions has been as fundamentally important as the industrial synthesis of ammonia from its elements. Lives of the world's 6 billion people might be actually better without Microsoft Windows and 600 TV channels, and neither nuclear reactors nor space shuttles are critical determinants of human well-being. But the single most important change affecting the world's population—its expansion from 1.6 billion people in 1900 to today's 6 billion—would not have been possible without the synthesis of ammonia.

In order to understand the significance of the link between the world's population growth and the synthesis of a pungent, colorless gas composed of one nitrogen and three hydrogen atoms (appendix A), it is necessary to appreciate first the *yin-yang* nature of nitrogen's biospheric presence. The element is abundant in the biosphere, making up almost 80% of the atmosphere's volume, yet its usable forms are scarce; and although living organisms need it in only small quantities, its shortage is commonly the most important factor that limits both crop production and human growth. This paradox arises from nitrogen's exceedingly stable atmospheric presence as a nonreactive N_2 molecule—and from the paucity of natural ways of transforming this recalcitrant dinitrogen into reactive compounds.

The bulk of living matter is made up of polymerized sugars or alcohols (cellulose, hemicellulose, and lignin) organized in wet tissues. Carbon, making up nearly half of these compounds, is the principal structural element of life, the supplier of quantity: in the biosphere it is about 100 times more abundant than nitrogen, which is a key provider of quality. Although relatively scarce, nitrogen is present in every living cell; in chlorophyll whose excitation by light energizes photosynthesis (the biosphere's most important conversion of energy); in the nucleotides of nucleic acids (DNA and RNA), which store and process all genetic information; in amino acids, which make up all proteins; and in enzymes which control the chemistry of the living world. Consequently, Arthur Needham did not exaggerate the element's importance when he wrote that "every vital phenomenon is due to some change in a nitrogen compound and indeed in the nitrogen atom of that compound."[1] Nitrogen's abundance in plants cannot be missed: it is the nutrient responsible for the vigorous vegetative growth, for the deep green of the leaves, for their large size and delayed senescence, as well as for the size and protein content of cereal grains, the staples of mankind. Nitrogen deficiency cannot be missed either: pale green or yellowing leaves, slow and stunted plant growth, low yields and depressed protein content of seeds.

Nitrogen's importance for human beings is no less critical. We have to ingest ten complete, preformed essential amino acids in order to synthesize our body proteins needed for tissue growth and maintenance. Stunted mental and physical development are the starkest consequences of protein malnutrition. Agricultural crops supply almost $\frac{9}{10}$ of those essential amino acids in food proteins, directly in staple cereal and legume grains, indirectly in animal foods; the remainder of dietary proteins comes from foods derived from grassland grazing and from aquatic species. But while photosynthesis draws readily on fairly small stores of CO_2 in the atmosphere to get the needed carbon, atmosphere's huge dinitrogen store is highly nonreactive, and availability of reactive nitrogen is almost always the most important factor limiting the yields in intensive agricultures.

N_2 molecules must be split into their two constituent atoms before they can be incorporated into an enormous variety of organic and inorganic compounds. Lightning is the only physical process that can fix substantial amounts of nitrogen, that is, to split the tightly bound molecule so the freed atoms can form reactive compounds. Although we cannot pinpoint the annual flux of this high-energy fixation, its global contribution clearly falls far short of agriculture's nitrogen needs. And there is only one group of living organisms capable of nitrogen fixation: about 100 bacterial genera, most notably *Rhizobium* bacteria associated with the roots of leguminous plants.

Not surprisingly, agricultures have been preoccupied with manipulating the flows of reactive nitrogen. Traditional farming relied on a combination of increasingly intensive recycling of organic wastes and cultivation of leguminous plants, but these inputs were insufficient to sustain high crop yields over large cultivated areas. As the concerns about future nitrogen shortages intensified during the latter half of the nineteenth century, chemists tried to prepare ammonia, the simplest of all nitrogen compounds, from its elements.

Industrial synthesis of ammonia thus does not belong to that fascinating class of serendipitous inventions: the compound just did not appear by accident in somebody's laboratory. Its synthesis from nitrogen and hydrogen was sought for more than 100 years, and by the beginning of the twentieth century it became one of the holy grails of synthetic inorganic chemistry. We can pinpoint—much like with Edison's lightbulb or the Wright brothers' flight—the time of the decisive breakthrough. Archives of Badische Anilin- & Soda-Fabrik (BASF) in Ludwigshafen contain a letter that Fritz Haber, at that time a professor of physical chemistry and electrochemistry at the Technische Hochschule in Karslruhe, sent on July 3, 1909, to the company's directors. In it he described the events of the previous day, when two BASF chemists came to witness the first successful demonstration of the synthesis in his laboratory.

Haber's invention was translated with an unprecedented rapidity into a commercial synthetic process by Carl Bosch. The Haber–Bosch process was the breakthrough that removed the most ubiquitous limit on crop yields, opening the way for the development and adoption of high-yielding cultivars and for the multiplication of global harvests. Today's ammonia synthesis has been greatly improved in many details and it operates with much higher energy efficiencies; but Haber and Bosch would easily recognize all principal features of their invention. Global output of ammonia is now about 130 million tonnes (that is, about 110 million tonnes of fixed nitrogen), and $^4/_5$ of it go into fertilizers, of which urea is by far most important.

Rich countries could fertilize much less by cutting their excessive food production in general, and by reducing their high intakes of animal foods in particular—but even the most assiduous recycling of all organic wastes and the widest practical planting of legumes could not supply enough nitrogen for land-scarce, poor, and populous nations. All the children to be seen running around or leading docile water buffaloes in China's southern provinces, throughout the Nile Delta, or in the manicured landscapes of Java got their body proteins, via urea their parents spread on bunded fields, from the Haber–Bosch synthesis of ammonia. Without this synthesis about $^2/_5$ of the world's population would not be around—and the dependence will only increase as the global count moves from 6 to 9 or 10 billion people.

Without synthetic ammonia today's global population would not stand at six billion people, but the process also raised the human intervention in the nitrogen cycle to an entirely new level. Ammonia is now one of the two most important synthetic compounds, and the ammonia industry is comprised of hundreds of mostly large plants that feed subsequent syntheses of various nitrogen fertilizer compounds. An adult contains about 1 kilogram of nitrogen in body tissues, but in many countries annual fertilizer applications now prorate to more than 50 kilograms of nitrogen per capita (the global mean is about 13 kilograms).

While the world's population stores no more than about 6 million tonnes of nitrogen (less than one-billionth of the atmosphere's enormous nitrogen stores), in order to maintain, and to gradually expand, this negligible reservoir, the reactive nitrogen in synthetic fertilizers is now perhaps equal to half of the total fixed by all bacteria in all natural terrestrial ecosystems. Moreover, in every intensively cultivated region, and especially where large-scale agriculture neighbors cities and industry, inputs from human activity are greatly surpassing natural flows of fixed nitrogen. On smaller scales, from local watersheds to individual fields, they dominate natural flows by more than an order of magnitude.

Transformations of these nitrogen inputs intensify the rates of microbial processing and increase the atmospheric emissions and deposition of nitrogen compounds and their leaching to fresh and coastal waters. We are thus fertilizing not just fields but, indirectly, also many natural ecosystems—and interfering in nitrogen's natural flows to a much higher extent than in the case of other biospheric cycles.

The fascinating story of nitrogen thus has many facets, many beginnings, and many consequences: traditional agronomy and modern biochemistry, ancient knowledge of valuable legumes, the creation of new industry at the beginning of the twentieth century, the quest for food self-sufficiency and prosperity, and large-scale environmental changes with consequences ranging, literally, from deep wells to the stratosphere.

All of these realities will be taken up in considerable detail in this book. I will first describe nitrogen's unique and indispensable status in the biosphere, its role in crop production, and the traditional means of supplying the nutrient. Then I will concentrate on various attempts to expand natural nitrogen flows by introduction of mineral and synthetic fertilizers. The core of the book is a detailed narrative of the epochal discovery of ammonia synthesis by Fritz Haber and its commercialization by Carl Bosch and BASF.

Subsequent chapters trace the emergence of the large-scale nitrogen fertilizer industry and its various products and analyze the extent of global, and national, dependence on the Haber–Bosch process and its biospheric consequences. I close by looking back—and looking ahead—at the role of nitrogen in civilization. And, in a sad coda to the story, I attach a short postscript describing the lives of Carl Bosch and Fritz Haber after the discovery of ammonia synthesis.

By trying to make the book as comprehensive, and as interdisciplinary, as possible, I recognize that I made its reading harder, or less interesting, for many people who are only curious about some parts of the whole. They should go ahead and create their own books within the book: agronomists can concentrate on chapters 1–3 and 7–9, ecologists on chapters 1–2 and 8–10, historians of technology on chapters 2–6. My hope is that both kinds of readers—those who skip some chapters, and those who persevere and read the whole book—will get new perspectives on how the synthesis of ammonia from its elements came about, and how its diffusion has transformed the world and enriched the Earth.