1 Dependence on Nitrogen

The Most Famous Field in the World

John Bennet Lawes made two significant decisions in 1843. He started an experiment with winter wheat on Broadbalk field, which was part of his estate at Rothamsted (Fig. 1.1). And he appointed Joseph Henry Gilbert, a chemist with a doctorate from the laboratory of the celebrated Baron von Liebig, to supervise the chemical analyses and advise on the design of experiments. The latter proved to be an excellent decision, with Gilbert's meticulous attention to detail providing an ideal foil to Lawes's intuitive flair. The partnership, one of the greatest in British science, lasted the 57 years until Lawes died in 1900. Gilbert died a year later.

Fig. 1.1. Harvesting wheat by hand on Broadbalk, probably in the 1860s. The self-binder was not introduced until 1902. (Photograph courtesy of Rothamsted Research.)

Box 1.1. Description of the soil of Broadbalk field.

The soil of Broadbalk field was classified as Batcombe Series by Avery and Bullock (1969). About 70% of the field is 'typical Batcombe' Series, a flinty clay loam to silty clay loam containing 18–27% clay, overlying mottled clay-with-flints containing about 50% clay within 80 cm of the surface. The rest of the field is either a heavier variant of the Batcombe Series, a flinty silty clay loam with gravelly or chalky material in the subsoil, or Hook Series, a slightly flinty silty clay loam. The pH of the topsoil is 7.5–8.0, and it contains about 1% organic carbon in plots receiving mineral fertilizer and 2.7% in plots that have long received farmyard manure. The site has only a very slight slope but is free-draining.

Because of Gilbert's appointment and the establishment of the Broadbalk Experiment, the history of Rothamsted dates from 1843. When, 125 years later, the then director of Rothamsted Sir Frederick Bawden described Broadbalk as 'the most famous field in the world' (Bawden, 1969), nobody argued. It is certainly the longest-running field experiment. At the time of writing, the 160th year of Broadbalk has just passed and the experiment remains useful for studying not only nitrate leaching (Goulding *et al.*, 2000) but also other environmental issues such as phosphate loss (Heckrath *et al.*, 1995) and the build-up of organic contaminants (Jones *et al.*, 1994), unforeseen in 1843. Its soil is described briefly in Box 1.1.

The Broadbalk Experiment

Lawes and Gilbert's experiment on Broadbalk has not changed greatly since 1843. However, in the first 3 years the plots were arranged to answer specific points, which the experimenters soon realized to be a mistake, and after the fourth year the emphasis was on continuity. By 1852, the present pattern had emerged and remained unchanged until 1967 (Johnston and Garner, 1969). This involved growing winter wheat continuously on plots that received either:

- No fertilizer.
- Minerals (P, K, Na, Mg) only.
- Minerals with four different additions of nitrogen, 43, 86, 129 or 172 lb/acre (48, 96, 144 or 192 kg/ha) as ammonium sulphate. Sodium nitrate was also tested for some applications in some years.
- Farmyard manure.

The main difference in the experiment today is that two extra additions of nitrogen (240 and 288 kg/ha) are now made. These reflect the much increased use of nitrogen by today's farmers, although the original additions were huge by the standards of 1843. Even by 1957, the average nitrogen application to winter wheat by farmers was only 75–90 kg N/ha (Garner, 1957). It could be said that Lawes was looking a long way ahead.

Box 1.2. Sir John Bennet Lawes, 1814–1900.

John Bennet Lawes was very much a Victorian in that he was an exact contemporary of the queen. He was 22 when Victoria came to the throne and he died a few months before her. He was unquestionably an eminent Victorian, though not among those listed by Lytton Strachey. Lawes is known as the founder of Rothamsted Experimental Station and for the contribution he made to agricultural science with his colleague Sir Joseph Henry Gilbert. The Broadbalk experiment and the Drain Gauges are mentioned in this book, together with the first recognition of the roles of mobile and immobile water in solute transport, but there was much more besides, several other field experiments and some notable work on animal nutrition. Lawes was also an entrepreneur, founding with little capital one of the first fertilizer businesses in the world and running it profitably for 30 years, before selling it and using one-third of the profits to set up the Lawes Agricultural Trust to maintain the experiments. He became in his later years a father figure in British agriculture, providing sound guidance in difficult times and looking ahead to future problems. Parish magazines of the era record him as a popular figure, and often benefactor, in Harpenden. Lawes was also a man with a social conscience, a model employer. He set aside land for allotments for workers on the estate, so that they could grow their own vegetables, and started a pig club. He also built a club-house by the allotments where those who toiled could buy a pint of beer more cheaply than elsewhere and were under no pressure to buy more than they wanted. Lawes and the club-house were celebrated by the novelist Charles Dickens in 'The Poor Man and his Beer', an article published in *All the Year Round* magazine in April 1859.

The Broadbalk Experiment was to play a key role in a famous dispute of its day.

Lawes and Liebig

Science thrives on disputes and in the mid-1840s there was a vigorous dispute over the source of the nitrogen used by plants between Lawes (Box 1.2) and Justus von Liebig (Box 1.3). On the face of it, the dispute was somewhat unequal. Liebig was one of the leading scientists of the day and the older of the two, as well as being a baron. Lawes was only 31, had left Oxford without bothering to take a degree and, worse still, was 'in trade'. He had started up a successful enterprise, but *in fertilizers*. By the standards of the day, he was socially greatly inferior to a baron, who doubtless was of independent means.

Lawes's biographer George Dyke records the dispute as starting in 1845 (Dyke, 1993). Liebig had already established the important fact that plants obtained their carbon from the air rather than the soil, as had previously been thought. Perhaps because of this he did calculations of the deposition of ammonia in rainfall, on the basis of which he wrote, in 1845, that 'the supply of ammonia to most of our cultivated plants is unnecessary, if only the soil contain a sufficient supply of mineral food'. By mineral food he meant phosphate, potassium, sodium and magnesium. Dyke (1993) records

Box 1.3. Baron Justus von Liebig, 1803–1873.

Justus von Liebig was the foremost agricultural chemist of his time, famous for the Law of the Minimum, the idea that plant growth is limited by the element least available in the soil. He was notable too for his realization that, although carbon dioxide makes up only 1% of the atmosphere, plants obtain their carbon from the air and not from the soil, as previously thought. Liebig was among the first scientists to achieve some kind of understanding of the nitrogen cycle. His almost correct ideas on crop mineral nutrition and his failure to realize that not enough ammonia was deposited in rain to supply the needs of crops are discussed in the main part of Chapter 1.

Liebig's contribution went far beyond agricultural chemistry. He and his friend Wöhler were among the founders of organic chemistry (Box 2.2) and provided improved methods of organic analysis. Liebig discovered chloroform and chloral and introduced the theory of radicals, the idea that a group of atoms forming part of a molecule could act as a unit and take part in chemical reactions without disintegrating, yet be unable to exist alone. Examples include the methyl radical $-CH_3$ and the carboxyl radical $-COOH$. He was also notable for founding a chemical laboratory at Giessen in Germany which he used to train young chemists (among whom was Joseph Henry Gilbert). Liebig must be given some credit for the strength of chemistry in Germany in the latter part of the 19th century. Indeed, his contribution to the subject must have been part of the intellectual heritage that underpinned the development of the Haber–Bosch process.

that Lawes flatly disagreed and wrote in 1846, 'There cannot be a more erroneous opinion than this, or one more injurious to agriculture'. This remark was hardly designed to placate, but it was in the context of an argument with enormous consequences. Liebig claimed that the fields of England were in a state of progressive exhaustion by removal of phosphates. Lawes agreed about the progressive exhaustion but believed it was caused by ammonia carried off in the grain (Dyke, 1991). The underlying problem was that Liebig seriously overestimated the concentration of ammonia in the atmosphere and this ultimately lost him the argument. However, his ideas about minerals, which were based on the composition of crop ash, were largely correct.

Dyke (1993) commented that, 'Liebig was stronger on matters of theory than on practical tests. Lawes and Gilbert had the mixture of both approaches that is the mark of the best scientists in all subjects'. By the autumn of 1844 they also had the results of the first simple experiment on Broadbalk. If Liebig was right, the plots given just minerals on Broadbalk would have out-yielded those without, and the 'minerals+nitrogen' plots would have done no better than the 'minerals only' plot. Table 1.1, based on a report by Garner and Dyke (1969), gives the results of that first experiment, which was designed to address this point, together with means from the experiments from 1856 to 1863 which followed the pattern started in 1852. Even the first simple experiment suggested strongly that Liebig was wrong and the later results confirmed this. Minerals alone did not give much more yield than no manure at all, while 'minerals+nitrogen' clearly

Table 1.1. Yields in early experiments on Broadbalk by Lawes and Gilbert. (From Garner and Dyke, 1969.)

Treatment	Yields Grain	(cwt/acre) Straw
The first harvest in 1844		
No manure	8.2	10.0
14 t farmyard manure	11.4	13.2
Ash from 14 t farmyard manure	7.9	9.9
Minerals only[a]	9.0	10.3
Minerals + 65 lb/acre ammonium sulphate[b]	11.4	12.7
Mean yields, 1856–1863		
No manure	8.8	8.3
Minerals only[a]	10.6	16.1
400 lb/acre ammonium salts only[b]	13.1	22.6
Minerals + 400 lb/acre ammonium salts[b]	21.5	37.3

[a] Minerals were P, K, Na, Mg.
[b] 65 and 400 lb/acre correspond to 73 and 447 kg/ha respectively.

out-yielded minerals alone. Lawes and Gilbert also tested Liebig's patent wheat manure but found it to have no effect (Johnston and Garner, 1969).

Baron von Liebig was not amused. In a confidential letter to a friend quoted by Smil (2001), Liebig wondered how 'such a set of swindlers' could produce research that is 'all humbug, most impudent humbug'. Had he known of the letter, Lawes could have retorted that one of the swindlers had been trained in Liebig's own laboratory. In fact, according to Dyke (1993), Lawes's attitude was entirely courteous. He took pains to preface all criticism of Liebig with a tribute to his contributions to the subject, but the courtesy was not returned. Indeed, Dyke commented that 'some of [Liebig's] writings were simply spiteful', and this seems to be confirmed by Smil. It is hardly surprising that Lawes could not bring himself to use the 'von' when writing of Liebig.

In public Liebig maintained that the Rothamsted results supported his theory. The ammonium fertilizer, he said, acted as a 'facilitator' for the adsorption of the minerals by increasing their solubility. But other Rothamsted results showed that clover grown without any 'facilitation' from ammonium fertilizer removed more minerals than the grain crops did – and took up more nitrogen.

Lawes emerged from the controversy as a man of principle, and certainly not a swindler. He made his living from the sale of phosphate fertilizers (through the Lawes Chemical Company), but when his experiments showed that additions of nitrogen rather than phosphate caused the greatest increase in yield in wheat, he did not hesitate to publicize the fact.

Smil (2001) mentions a rather delightful irony. Whilst propagating his 'minerals' theory, Liebig had told the British prime minister Sir Robert Peel in 1843 that 'the most indispensable nourishment taken up from the soil is the phosphate of lime'. This was, of course, just what the Lawes Chemical Company was selling, but Lawes would shortly be telling the world that nitrogen was the nutrient that had the greatest impact on grain yields. Dyke (1991) notes that, in 1864, Professor J.T. Way commented in an answer to a Select Committee of the House of Commons, '... but there is one great peculiarity in Mr Lawes's career, which is this, that for a great many years he spent a large sum of money annually in making agricultural experiments; and, on the whole, I believe that those experiments, although he has freely reported them to the public, have not been in favour of his trade and position as a manure merchant, but rather to the contrary'.

This story has a sad postscript. I worked for the Lawes Chemical Company in 1965–1966, a few years before it ceased to be an independent company. One reason why the company was not doing well was that it did not have an independent source of nitrogen for its compound fertilizers, those incorporating nitrogen, phosphorus and potassium. It was still obtaining ammonium sulphate from the nearby Becton gas-works, but this was sold by the specialist 'Straights' division of the company which sold single-nutrient fertilizers. For the much larger quantities of nitrogen the company needed for compound fertilizers, it was buying in urea from ICI, and this put it at a disadvantage in an increasingly competitive market, at a time when the government subsidy on fertilizers was to be removed in 1966. The manufacture of nitrogen fertilizers had changed far more than that of phosphate and potassium fertilizers and the scale of production mattered. The Lawes company was not a large one by comparison with its competitors.

The dispute between Liebig and Lawes was only the beginning of the arguments about nitrogen fertilizer, and, with hindsight, we can see in those results from Broadbalk the seeds of the current debate about nitrogen fertilizers.

Why did the Broadbalk wheat crop respond so much to nitrogen?

Nitrogen has many functions in plants. It is found in the chlorophyll that they need for photosynthesis, the nucleic acids in which the programme for their growth and development is encoded, all plant proteins, the enzymes that catalyse all biochemical processes and, not least, the walls that hold the cell together. Much of the biochemistry of life involves nitrogen-containing chemical compounds. Plants with insufficient nitrogen tend to be stunted, yellowish and generally sickly.

Nitrogen augments yield by increasing the leaf area within which photosynthesis takes place. It does so by increasing both the rate at which cells multiply and the surface area of each cell. It also boosts the number of leaves, but plants vary in the way they achieve this. Cereal plants, such as wheat and barley and the grasses to which they are related, produce extra shoots, known as 'tillers'. These probably evolved as a means of exploiting favourable growing conditions and many of them die off if nutrients are in short supply. Applying nitrogen increases the number of tillers that survive, providing extra leaves, more stems and a greater yield. Plants such as potatoes with a more complex leaf structure produce extra branches and leaves in response to extra nitrogen.

Nitrogen also extends the duration of the leaf cover. As older leaves die they release their nitrogen to benefit younger leaves or the developing grain or tubers. Applying nitrogen delays the dying-off of the leaves and maintains a greener, leafier plant.

What benefit did the 'minerals' give?

Phosphate has a key role in the building of the nucleic acids that are central to the growth and development of the plant. It is also very much involved in the storage and use of energy in cells. The adenosine triphosphate system could be said to be the plant's 'energy currency', and other phosphate systems play a vital role in plant function. Potassium has an important role in the mechanism by which carbohydrates are distributed in the plant from the point of production in the leaves to the point of use at growth points. It helps the plant to use water efficiently and to maintain its osmotic and electrical balance, and it is also an enzyme activator. Magnesium is a key constituent of the chlorophyll molecule and it too is an enzyme activator. Calcium plays a part in the structural tissue of the plant and is also involved in cell division and in maintaining the integrity of membranes. Sulphur was not included among the minerals by Liebig, but it is a constituent of certain key amino acids and proteins. It is important for the production of oils in plants and it has been supplied as a fertilizer for oilseed rape in the UK since about 1993 following the removal of most of the sulphur from the emissions of British power stations. About 30% of the British oilseed rape crop now receives it. Iron was also not included the minerals. It is essential for plant growth but not in the same quantities as the other nutrients mentioned. It falls between the major nutrients and the trace elements mentioned below.

Several other nutrients, the 'trace elements' copper, zinc, manganese and boron, are necessary to the plant but only in small quantities. Other trace elements, such as chromium, selenium, iodine and cobalt, are not essential to plants but are essential to animals grazing on the plants. The trace elements copper and zinc, together with nickel, which is not a trace element, become pollutants when too much is there, often after long-term applications of sewage sludge. The trace element then becomes a 'heavy metal'. This is something of a misnomer, because these 'heavy' metals have smaller atomic weights than many other metallic elements, but lead is a heavy metal in both senses.

Apart from nitrogen, the two main nutrients applied in fertilizers are phosphate and potassium. Cereal crops do not need large applications of these nutrients, but potatoes and other crops that form large storage organs need both nutrients. This is as much a matter of arithmetic as plant physiology. A crop of 60 t/ha of potatoes contains roughly 13 t/ha of dry matter, of which about 2% is potassium, so around 260 kg/ha of potassium will need to be supplied as fertilizer or manure just to replace what has been removed from the soil by the tubers. (Most of the potassium in the rest of the plant will have been translocated into the tubers.) Trace-element fertilizers tend to be needed in particular areas, manganese on highly organic soils in the fens and boron for sugarbeet on sandy soils in East Anglia, for example.

The Build-up in Nitrogen Fertilizer Use

1800–1900

Chapter 4 suggests that gas liquor from coal gas production was the first 'chemical' or non-organic nitrogen fertilizer to be used, and that it probably came into use in about 1810–1820. Ammonium salts were made by acidifying gas liquor by at least 1841 and probably earlier, and by 1900, large amounts of ammonium sulphate were produced in this way (Fig. 1.2). By the 1860s ammonium sulphate was also made from ammonia generated in coking ovens (Chapter 4) as well; this process had become important by 1900 (Fig. 1.2) and continues today.

In the 1830s and 1840s, two further sources became available, guano and Chilean nitrate (Chapter 4). Of these, the Chilean nitrate was much the more important (Fig. 1.2) because it produced far more fertilizer nitrate than guano, and also nitrate for explosives, which guano did not provide. Also,

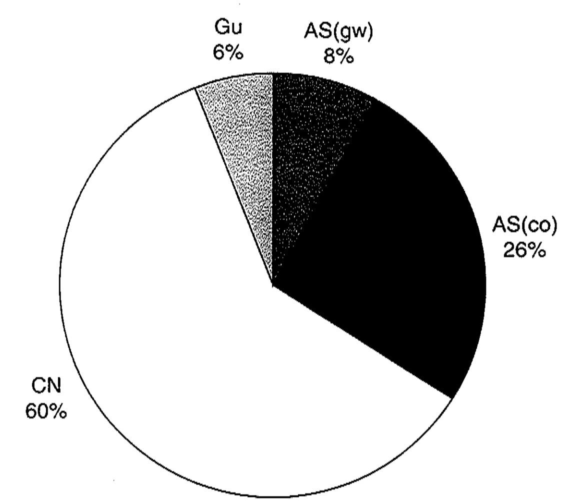

Fig. 1.2. Relative importance of ammonium sulphate from gas-works (AS(gw)), ammonium sulphate from coking ovens (AS(co)), Chilean nitrate (CN) and guano (Gu) as fertilizer sources in 1900. (Based on data from Smil, 2001, pp. 50–51 and p. 240.)

the supply was never exhausted and some production continues to this day. The supply of guano was exploited greedily and contributed in a major way to fertilizer supplies for only about 30 years, from 1842 to 1872 (Fig. 1.2).

Smil (2001, p. 245) calculated that during the second half of the 19th century the world's cumulative production of nitrogen fertilizer was 360 kt of N, of which 220 kt was from Chilean nitrate, 20 kt from guano, and 120 kt of ammonium sulphate from coking. Smil's table did not include gas liquor or ammonium sulphate produced from it, probably because there were no records and such records might have been of limited use because of the variable nature of the product.

1900–2000

Between 1900 and 1980 there was a remarkable increase in the production of nitrogen fertilizers. This is shown in Fig. 1.3, which is based on Appendix L of Smil (2001, p. 245). The term 'exponential increase' is sometimes used rather loosely, but its use here is entirely correct. Production (P) was related very exactly to the number of years after 1900 (t) by the exponential relationship $P = 274 \exp(0.0651t)$.

For the statistically minded, the relation was sufficiently exact to give an r^2 value greater than 0.98 for 13 degrees of freedom. This rate of increase was not sustained, and beyond 1980 production continued to increase but fell away from the exponential relation for the first 80 years of the century. It was in the early 1980s that fertilizer use reached a plateau in the UK (Fig.

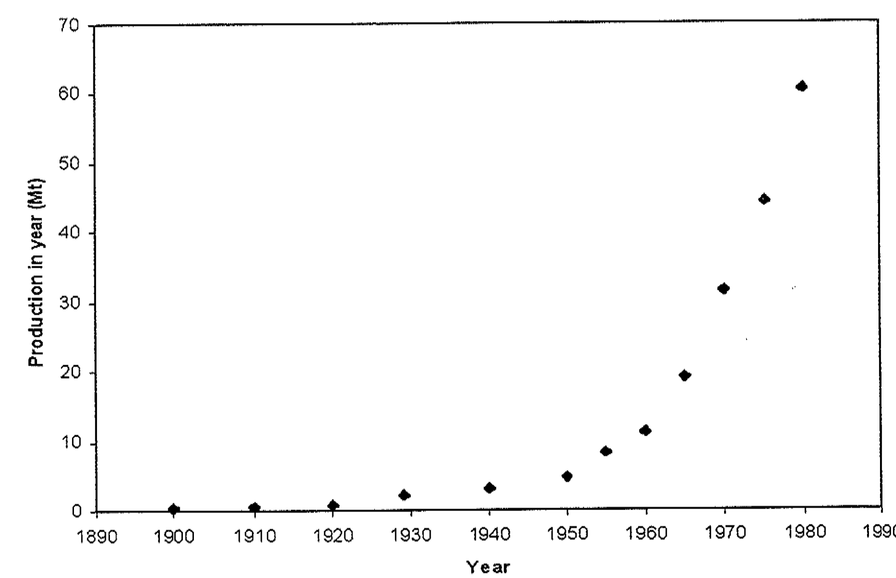

Fig. 1.3. The exponential increase in world fertilizer production between 1900 and 1980. (Based on Appendix L of Smil, 2001, p. 245.)

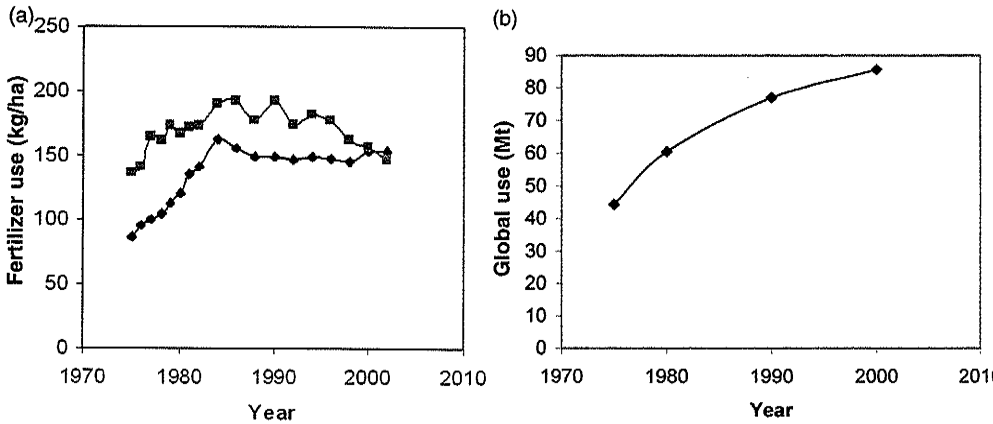

Fig. 1.4. Aspects of the plateau in fertilizer production, 1980–2000. (a) Average applications of fertilizer N in the UK to all tillage (♦) and grass leys of less than 5 years (■). (Data provided by Chris Dawson.) (b) World production of N fertilizer. This is the continuation of the curve in Fig. 1.3. (Data from Appendix F of Smil, 2001, p. 245.)

1.4), and the same was probably broadly true in other Western European countries and North America.

Smil's Appendices F and L show that global production of nitrogen fertilizer rose 238-fold, from 360 kt of fertilizer N in 1900 to 85,700 kt in 2000. Figure 1.5, based on the same Appendices, shows the percentage of N fertilizer production that was achieved by the Haber–Bosch process described in Chapter 4. This increased from zero in 1900 (before the process was invented) to more than 99% in 2000. The latter is a statistic to note. It reflects the increasing dominance of this process in the production of nitrogen fertilizer and, viewed from a different angle, it shows how dependent the world has become on this process.

Dependence on the Haber–Bosch Process?

Smil (2001) and Jenkinson (2001) have drawn to our attention that the population of the world is now collectively dependent on nitrogen fertilizer produced by the Haber–Bosch process. Smil provided two key calculations.

The first concerns staple crops grown intensively on large areas of land, the yields of which could not be maintained without applications of synthetic nitrogen fertilizers. (Synthetic means 'manufactured from its elements' – an exact description for nitrogen from the Haber–Bosch process, as we shall see in Chapter 4.) Smil (2001, p. 155) argued that these fertilizers now provide between 60 and 80% of the nitrogen for the most widely grown staple crops, and that the Haber–Bosch process has recently been supplying about half of the nitrogen input into the world's agriculture. Other things

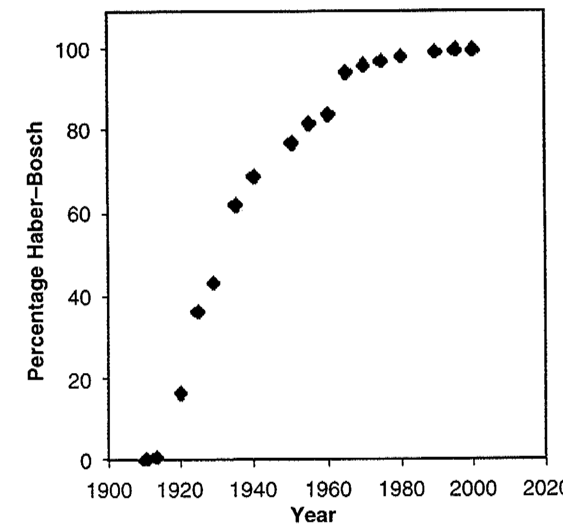

Fig. 1.5. The increase in the percentage of global nitrogen fertilizer produced by the Haber–Bosch process, 1910–2000. (Data from Appendix L of Smil, 2001, p. 245.)

being equal, the world's harvest of staple crops would be halved if nitrogen fertilizer was taken away.

This does not mean that half of all the food produced today would be unavailable or that half the world's population would not be alive without nitrogen fertilizer. Most of us do not eat just staple crops, we eat meat and dairy products as well. The animals that supply these commodities also eat the staple crops, together with grass, which may or may not be fertilized. We also eat fish. It requires, as Smil put it, 'further disentangling of nitrogen's complex pathway in the global agroecosystem'. He has done the 'further disentangling', and his conclusions make stark reading:

> In 1900 the virtually fertilizer-free agriculture (less than 0.5 Mt were applied to crops world wide) was able to sustain 1.625 billion people by a combination of extensive cultivation and organic farming on a total of about 850 Mha. The same combination of agronomic practices extended to today's 1.5 billion hectares would feed about 2.9 billion people, or about 3.2 billion when adding the food derived from grazing and fisheries. This means that only about half the population of the late 1990s could be fed at the generally inadequately per capita level of 1900 diets without nitrogen fertilizer. And if we were to provide the average 1995 per capita food supply with the 1900 level of agricultural productivity, we could feed only 2.4 billion people, or just 40% of today's total.
>
> (Smil, 2001, p. 159)

In short, without synthetic nitrogen fertilizer, agriculture could support only half as many people as are alive today, and then with very basic, predominantly vegetarian diets. Today's average diets could be supplied to only 40% of the population. Collectively we can no more give up nitrogen from the Haber–Bosch process than an addict can give up heroin. The removal of our 'drug' would cause widespread trauma and death.

But what of the future? Smil (2001, p. 175) took the medium version of the UN's long-term population projection which predicts an increase in world population of 3 billion between 2000 and 2050, virtually all in low-income countries. These countries will need to use at least 85% more synthetic nitrogen fertilizer than they do today just to maintain their present average diets. Eliminating malnutrition might need an extra 10% and producing more animal foods a further 10%, with the result that low-income countries may double their 1995 nitrogen fertilizer consumption by 2050. Assuming no change in fertilizer use in the affluent world, which is probably reasonable, Smil calculated that the world might use 140 Mt of N from synthetic fertilizers by 2050. This would mean that the Haber–Bosch process would supply 60% of the nitrogen feeding the world's crops and therefore be essential to the basic nutrition of about 60% of the world's population. Nearly all the protein needed by the 2–4 billion children to be born in the next two generations will have to come from it. Barring some hugely significant technological development or some unimaginably awful human catastrophe, our dependency on synthetic nitrogen fertilizer is set to increase.

Smil (2001) has given us the large-scale picture, painted with a broad brush. There is some detail omitted. Political upheavals also affect the consumption of nitrogen fertilizer. Fertilizer use declined sharply in Eastern Europe after the Berlin Wall fell and the Soviet command economy collapsed. So do fluctuations in supply and demand. There was a surplus of fertilizer produced in the early 1980s in both North and South America and in Western Europe (Jenkinson, 2001) as applications (Fig. 1.4a) levelled out. This led to decreases in prices and a reduction in investment in new plant (Bumb, 1995). These events must have contributed to the falling away of production in the 1980s from the exponential relation for the first 80 years of that century (Fig. 1.3). These details, however, do not greatly change the overall picture of increasing dependence on the Haber–Bosch process or, the other side of the coin, the fundamental importance of this process to humankind.

Dependence on synthetic nitrogen fertilizer causes problems, as do other forms of dependence. Using it inevitably tends to increase losses of nitrate from the soil to natural waters, where it causes concern about the quality of the environment and the health of those who drink the water. It also increases losses of the 'greenhouse gas' nitrous oxide to the atmosphere, which may in the long term prove to be a greater problem than nitrate in water (Jenkinson, 2001).

The environmental problem is complex. Nitrate is rarely lost from the soil in any great quantity directly from nitrogen fertilizer. Much of the added nitrogen is removed in the crop and most of the rest is left in the soil as organic residues. Losses of nitrate usually arise after harvest when soil microbes break down the residues. Substantial amounts of nitrate enter the environment from sources other than fertilizer application. Road traffic and industry both generate nitrogen oxides, which are either deposited as

nitrate or are converted to nitrate on deposition. Ammonia can be generated on one part of a farm and deposited on another. To add to the complexity, phosphate is usually responsible for algal blooms in fresh water but nitrate in coastal water. These topics are discussed further in subsequent chapters.

The health issue is also complex, and the conclusion reached by medical researchers (discussed in Chapter 9) that nitrate has several beneficial effects on human health may come as a surprise to some readers.

A state of dependence on synthetic nitrogen fertilizer is not desirable, but it is the state in which we find ourselves as we begin the 21st century. We have to ensure that there is enough food to go round, but we need to make sure that it is produced as efficiently as possible and distributed more effectively than it is at present. Efficiency implies optimizing the ratio of food produced to nitrate released into the environment, rather than just maximizing the yield or minimizing the loss of nitrate per unit area. It means recognizing the different problems and needs of farmers in the richer and poorer parts of the world. It also means determining with certainty in which environmental problems nitrate is the main factor, what role it plays and providing appropriate solutions. Finally, if, as seems increasingly likely, nitrate is beneficial to health rather than a threat to it, we need legislation that recognizes this fact. In short, we need to come to terms with nitrate.