6 Nitrogen in modern European agriculture

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There is no life without nitrogen. The element is an irreplaceable constituent of amino acids that are required for the assembly of proteins. These, in turn, provide building blocks of all metabolising tissues and of all enzymes that control the chemistry of life. Nitrogen is also present in the nucleotides of nucleic acids (DNA and RNA) that store and process all genetic information. Adults cannot synthesise eight amino acids found in proteins, and children need two more for their tissue growth. Consequently, these ten essential amino acids must be ingested in food – and hence agriculture, as Justus von Liebig (1840) so aptly noted more than 160 years ago, is all about producing digestible nitrogen.

Natural photosynthesis is a prolific fixer of carbon, with the global net primary productivity nearly 60 billion tonnes of it on land, and close to 50 billion tonnes in the ocean (Smil, 2002). But most of the terrestrial carbon is stored in woody phytomass as cellulose, hemicellulose and lignin: none of these abundant polymers contains any nitrogen, and except for the ruminants they are not digestible by mammals. Among uncultivated species only tree nuts and seeds of cereal and leguminous plants contain relatively large amounts of nitrogen because of their unusually high protein content. Eventual domestication of cereals and legumes became the nutritional foundation of all settled societies. Harvests of these crops were restricted by a variety of environmental (water, nutrients, pests) and management (tillage, weeding, crop rotations) factors, but in most traditional agro-ecosystems one limitation was nearly always the most common reason for low yields: inadequate supply of nitrogen.

I. Pre-1900 realities

During the early modern era (1500–1800) two regions at the opposite ends of the Eurasian continent – namely East Asia (coastal China, Korea and Japan) and Western Europe – experienced most acutely the combination of relatively high population densities and limited availability of additional good-quality farmland. Hence, they had the greatest stake in increasing crop yields. Traditional farmers had three ways in which to supply additional nitrogen to their crops: recycling of organic wastes (including crop residues, mainly straw, and animal and human wastes); practising crop rotations including nitrogen-fixing leguminous grains (beans, peas, lentils, soybeans); and planting of leguminous cover crops that were plowed under as green manures (Smil 2001). These cover crops included most commonly two clover genera (*Trifolium* and *Melilotus*) and several vetches (*Vicia*), but field peas (*Pisum*), chickpeas (*Cicer*) and lupines (*Lupinus*) were also used in some European regions (Pieters, 1927).

Traditional extent of crop residue and manure recycling was very similar in parts of East Asia and Western Europe. Typical French rates were around 20 t/ha, and the Netherlands were the early paragon of intensive manuring with as much as 30 t of manure applied annually per hectare of cropland. However, nitrogen content of this organic matter was low, as manures were often recycled only after many months, or even several years of storage, losing a large share of the nutrient through volatilisation and leaching. Post-applications losses were particularly high when the manures were spread during fall and winter and on bare, sloping land. These losses typically reduced the original nitrogen content by at least half, often by two-thirds and even by more than four-fifths of the initially voided nitrogen. As a result, nitrogen from recycled manures actually available to crops amounted often to just a few kilograms per hectare, or no more than the nutrient in atmospheric deposition.

Rotation of grain legumes (peas, beans, lentils) also left behind only small amounts of nitrogen (fixed by the symbiotic *Rhizobium* bacteria) for the subsequent non-leguminous crop. In contrast, cover legume crops, whose inclusion into often complex rotation schemes became more common only after 1750, could supply large amounts of the nutrient for the following cereal, tuber and oil crops. Rapid adoption of new cultivation schemes (the best known form example was the English Norfolk cycle of rotation that included wheat-turnips-barley-clover, but there were other similar sequences in other countries) led to higher nitrogen supply (Chorley, 1981). By the middle of the 19th century cover legumes (with clover dominant) commonly accounted for as much as a quarter of all planted area, or double the share before 1750, a change that had at least tripled the rate of symbiotic nitrogen fixation.

Consequently, Chorley (1981) suggested that this neglected innovation was comparatively as important as was steam power in Europe's economic development in the period of early industrialisation. A detailed nitrogen balance reconstructed for a large grain-and-dairy Dutch farm of the early 19th century shows the importance of symbiotic fixation: it was the largest nitrogen input (almost 50 kg N/ha), followed by the recycling of manure and animal droppings on the pasture (total of nearly 40 kg N/ha), and by the return of crop residues (about 20 kg N/ha) (Frissel, 1978). In total, about 3/4 of all nitrogen supply on this farm (about 100 kg N/ha) came from managed inputs, compared to no more than a third in a typical pre-1750 operation.

Two new options of nitrogen delivery emerged just before the middle of the 19th century: imports of guano (droppings of tropical birds that accumulated on arid tropical islands and contained up to 14percent N) and Chilean nitrate (Smil, 2001). While the deposits of high-quality guanos were largely exhausted by the 1870s, mining and processing of Chilean nitrates ($NaNO_3$ has 15percent N) continued to increase and by the year 1900 it reached 1.3 million tonnes (Mt). Western Europe, led by Germany and the UK, was the largest importer of this inorganic fertiliser, buying 65–70 percent of all exports during the last decades of the 19th century. In addition, by 1900 Germany and the UK were also the world's leading producers of ammonia recovered from coke ovens that were first introduced in Western Europe during the 1860s and 1870s and whose more efficient versions spread rather rapidly during the 1880s.

Western Europe's combination of organic recycling, imported guano and Chilean nitrate and newly available by-product ammonium sulfate was able to support the world's highest staple crop yields. In spite of this achievement the region was also the world's largest importer of wheat. Annual imports were about 5 Mt in the UK and almost 1 Mt/year in Germany, and there was no significant amount of potentially arable land to be converted to cropping. Given this reality it was not surprising that William Crookes (1899) made a much publicised appeal to the continent's chemists for coming up with a radically new method of securing agricultural nitrogen – or else facing a 'deadly peril of not having enough to eat' perhaps as early as the 1930s.

II. *Die gründer Jahre* (1900–1913)

This German subtitle is entirely appropriate as Crookes's fears were rather promptly allayed and the foundations of modern agricultural productivity and prosperity were laid down thanks to the perseverance, dedication and innovation of German chemists. The quest for the synthesis of ammonia, the simplest of all stable inorganic nitrogen compounds, was not an exclusively German affair: there were some notable pre-1900 contributions by French and English scientists, but the later German effort was decisive. In March 1900 Wilhelm Ostwald, at that time already one of the world's most respected chemists, notified the General Director of the Badische Anilin- & Soda-Fabrik (BASF) in Ludwigshafen that he succeeded in synthesizing NH3 from its elements in the presence of an iron catalyst. His claim was soon exposed as a contamination artifact, but by 1904 Fritz Haber, a young Privatdozent at the Technische Hochshule in Karslruhe began his work on the synthesis.

Haber, aided by Robert le Rossignol, experimented with different catalysts, pioneered the use of high pressure in the synthesis, and achieved acceptable reaction yield by recirculating the reagents (Stoltzenberg, 1994). After some inevitable setbacks he demonstrated his success to the BASF representatives in July 1909. A no less remarkable effort followed as Carl Bosch and his colleagues solved some unprecedented technical challenges and were able to transform the laboratory process into a full-scale commercial operation in just four years (Smil, 2001). The world's first synthetic ammonia plant began operating in Oppau near Ludwigshafen in September 1913, and the compound was used as the feedstock to produce solid fertiliser in the form of ammonium sulfate, $(NH_4)_2SO_4$.

III. A long interlude (1914–1950)

During these years both the Haber-Bosch synthesis of ammonia and applications of nitrogenous fertilised derived from the gas remained an overwhelmingly European affair. The WWI interrupted further expansion of ammonia synthesis for nitrogenous fertilizers but it led to the construction of the world's second ammonia factory at Leuna whose output was used, as was that of the Ludwigshafen plant since 1915, as the feedstock for the synthesis of nitrates needed for explosives. After the WWI several notable modifications of the Haber-Bosch process were developed in France (by Georges Claude), Italy (by Luigi Casale) and Germany (above all by Friedrich Uhde), but the BASF kept its primacy in ammonia synthesis during the 1920s, and Germany dominated its production. By1928 its annual output just surpassed 1 Mt NH_3, accounting for about 90percent of the world's total, but this ascent was followed by a sharp downturn, stagnation and slow growth that was brought by the global economic crisis: German output was nearly halved by 1931, and it surpassed the 1928 peak only by 1939.

But throughout this period Germany remained the leading user of new fertilisers in absolute terms, although their share in the country's total nitrogen supply remained low: during the 1930s, when manure remained the country's largest source of agricultural nitrogen (followed by biofixation), it amounted to less 20percent of the total and to no more than 20 kg N/ha in absolute terms (Smil 2001). Dutch agriculture was by far the most intensive pre-WWII user of nitrogen fertilisers, with applications averaging above

40 kg N/ha during the late 1930s, (Erisman, 2000) and reaching 50–60 kg N/ha in parts of the country. In contrast, the average US rate was less than 3 kg N/ha.

Throughout the 1930s European consumption of nitrogenous fertilisers remained above half of the world's total while the continent's arable land accounted for only 12percent of all cropland. But the applications were heavily concentrated in Germany, Benelux, England and France: although ammonia-based nitrates were commercially available throughout Europe, their applications outside the Northwestern part of the continent remained marginal. After a deep plunge of production during the WWII their synthesis and applications began to grow impressively only during the early 1950s, but a faster growth elsewhere began to erode Europe's primacy.

IV. Decades of expansion (1951–1989)

Large expansion of new ammonia production capacities during the 1950s was based on only incremental technical improvements. A fundamental cluster of technical innovations came only during the late 1960s when single-train natural gas-based plant equipped with centrifugal compressors (the first one was built by M.W. Kellogg in 1963) began replacing the multi-train coke-based process that relied on reciprocating compressors (Smil, 2001). The two most important consequence of this development were enormous energy savings in ammonia synthesis and rapidly rising average capacities of ammonia plants. During the early 1950s typical energy cost was above 80 GJ/t NH_3, a quarter century later they fell below 35 GJ/t for the best plants, and typical plant capacities rose from less than 200 t NH_3/day in the early 1960s to 1200–1400 t/day during the 1980s, when the largest plants surpassed 1600 t/day (Smil, 2001).

European consumption of nitrogenous fertilisers stood at 1.8 Mt N in 1950, 20 years later it reached 9.6 Mt N, more than quintupling in a generation, and it had expanded by almost 50percent during the 1970s; only then it slowed considerably, growing by only about 12percent between 1980 and 1988 when it peaked at 15.98 Mt N. For the EU15 the peak consumption took place three years earlier when the applications of 11.2 Mt N were 12percent above the 1980 level (FAO 2002). As a result of this virtually uninterrupted growth (there was only one year during the nearly four decades of expansion when the continent's total nitrogen consumption did not increase) Europe's share of global nitrogen applications remained disproportionately high when measured against the continent's share of arable land.

However, rising demand in North America, and later in Asia, reduced it from about 50percent in 1950 to about 38percent in 1960, to just over 30percent in 1970 and less than 20percent during the late 1980s when Europe cultivated roughly 10percent of the world's agricultural land. In relative terms average applications rose nearly tenfold between 1950 (about 12 kg N/ha) and 1988 when they peaked at 118 kg N/ha of arable land and permanent crops. The highest national rate rose twice as high as the continental mean: by the early 1980s the Dutch application averaged just over 250 kg N/ha and they were the highest in the world.

V. Recent contraction (1990–2002)

Two trends combined to bring Europe's total nitrogen applications from their peak of nearly 16 Mt N in 1988/89 to just 11.6 Mt N by the year 2000, roughly a 28 percent contraction. Collapse of the Communist regimes halved the applications in the central and eastern parts of the continent where all agricultural inputs, be they fertilisers or field machinery, were previously used with staggering inefficiency. And a more efficient use of the nutrient and, in some countries, environmentally driven limits on its use lowered the Western Europe's applications by nearly 20 percent. This shift brought the continent's share of the global use of synthetic nitrogenous fertilisers from 18 percent in 1990 to 15 percent in the year 2000, still about twice as high as Europe's share of the world's cropland.

This pullback lowered the average European applications to 99 kg N/ha by the year 2000, a nearly 20 percent from the 1988 peak, and the Dutch applications declined to about 185 kg N/ha by the year 1995. Although the Dutch had retained their global primacy China's nation-wide mean of the late 1990s was only about 5 percent below the Dutch average (China is now both the world's largest producer and user of nitrogenous fertilisers). And several Chinese provinces (above all Jiangsu and Guangdong), whose areas and populations are considerably larger than the Dutch national totals, are now ahead of the Netherlands, applying annually in excess of 250 kg N/ha of arable land (Smil, 2001). Moreover, Chinese and Dutch figures are not directly comparable, as virtually all of the Chinese fertiliser goes to crop fields, but a large share of Dutch nitrogen is spread on pastures.

VI. Consequences for food production

Europe's intensive fertilisation, whose post-1950 costs were increasingly supported by rising agricultural subsidies, was reflected in a steady growth of average crop yields. As already noted, staple grain yields in parts of the continent were the world's highest even before the discovery of ammonia synthesis. By 1900 wheat harvests were around 2 t/ha in the UK, as well as in the Netherlands and Denmark, and close to 2 t/ha in Germany. In contrast, they were only about 1 t/ha in the Austro-Hungarian empire, about 0.8 t/ha in Italy (that was also the US mean), and less than 0.6 t/ha in European Russia, the last rate being almost as low as the typical medieval mean in Western Europe.

Yields continued to increase after the WWI with higher nitrogen applications, but the gains became particularly impressive after the introduction of new, short-stalked cultivars during the 1960s. Again leading the world, Dutch wheat yields rose from 4.3 t/ha during the early 1960s to 7.3 t/ha two decades later, and English and French yields were not far behind. But the most remarkable development concerning the crop productivity began unfolding during the 1980s as the Western Europe's declining applications of nitrogen were not accompanied by declining harvests; instead, higher rates of the nutrient uptake were translated into slowly, but steadily, rising yields. One of the best illustrations of this trend was the British experience.

Europe increased yields naturally brought a higher degree of self-sufficiency in staple food production (EU has actually become a net exporter of wheat) but increasing demand for animal foods has led to rising imports of feedstuffs dominated by corn, soybeans and dried cassava. Continent's net imports of all feedstuffs were about 27 Mt in the year 2000, representing an addition of at least 6 Mt of protein whose metabolism by domestic animals further burdens Europe's environment.

VII. Changing diets

According to FAO's food balance sheets Europe has by far the highest per capita food availability in the world. The entire continent averages nearly 3,300 kcal/day and the EU mean was about 3,500 kcal/ day in the year 2000 (FAO 2002). Some poorer EU countries are actually ahead of the mean, with both Greece and Portugal just above 3,700 kcal/day, well ahead of France and Germany. Given the continent's ageing population (metabolic requirements decline with age) and the increasingly sedentary way of urban life, the actual daily food requirements range mostly between 1,500–2,000 kcal/capita for adult females and 2,000–2,600 kcal/capita for adult males, and weighted means for entire populations are rarely above 2,000 kcal/person. Large gaps between average availability and actual consumption – averaging daily more than 1,000 kcal/capita – can be accounted for by two major trends: overeating, leading to higher rates of obesity (although Europe has nowhere near the epidemic proportions of North American obesity) and increasing food waste (Smil, 2000).

Greatly expanded food production also led to some very important qualitative dietary changes, including a rapid transformation of Mediterranean diets that have been extolled for decades as perhaps the best choice for maximising longevity and minimising the risk of many chronic civilisational diseases including, most notably, cardiovascular illnesses. But by the end of the 20th century this desirable diet had become more of a myth than a reality in the region's most populous nations as typical Spanish and Italian ways of eating have been dramatically shifting in the direction of less salubrious Northern eating. This means (often rapidly) declining intakes of bread, fruit, potatoes and olive oil, and increasing consumption of dairy products and meat. Most notably, Spanish per capita supply of meat is now nearly six times higher than it was two generations ago, and the intake of animal fat is more than three times high.

So far, this shift has had no negative effect on Spanish health, resulting in a paradox of declining cardiovascular mortality even as intakes of meat and dairy (and hence of saturated fats) have been increasing, and consumption of olive oil and foods rich in complex carbohydrates has been dropping (Serra-Majem [et al.], 1995). The best explanation appears to be expanded access to health care, improved control of hypertension and reduced smoking; increased consumption of fruit and fish may be a contributing factor. However, a generation from now the outcome may be different.

VIII. Environmental impacts

Many traditional agricultures that did not practice intensive recycling and rotations with leguminous species were constantly mining soils by steadily reducing their nitrogen content. Large parts of the sub-Saharan Africa are now the most worrisome example of this degradation that reduces the productive capacity of agricultures. In contrast, as fields in Europe's intensively cultivated regions began to receive higher applications of nitrogenous fertilisers in addition to the recycled organic matter and to rising levels of atmospheric deposition, their nitrogen balance turned slightly positive, and eventually they became very substantial net recipients of the nutrient.

Already a generation ago a study of nitrogen balances that included 13 European agro-ecosystems found gains in soil organic nitrogen (the pool which usually contains more than 90percent of the nutrient present in soil) in 10 (76percent) of them, with annual increases adding commonly to 30–70 kg N/ha, and ranging as high as 280 kg N/ha (Frissel, 1978). However, without synthetic fertilisers most of these agro-ecosystems would have had net nutrient losses. Two more recent national agricultural nitrogen balance sheets, for Germany and the Netherlands, found average annual accumulations of, respectively, 47 and 38 kg N/ha (Smil, 2001). Obviously, gains are much higher in many of the most intensively cultivated regions.

Because of inevitable post-applications losses, the fertiliser nitrogen must be applied in amounts exceeding the nutrient requirements of crop. Actual uptakes of the nutrient by crops vary widely depending above all on climate, soils, crops grown and agronomic practices. European studies of nitrogen uptake efficiencies demonstrate the expected difference between the nutrient's utilisation in rainy Northwestern part of the continent and in much more arid Mediterranean climates (Jenkinson and Smith, 1989). High-yielding winter wheat recovered 39–57 percent of nitrogen from the applied urea and 38–70 percent from ammonia in France, 52–65 percent in England, and 52–62 percent in the Netherlands; in contrast, nitrogen uptakes ranged between 27–40 percent in Portugal, and only between 18–37 percent in Greece. Good approximations would thus use rates of 55percent for the best applications, 45percent for standard good practices, and 35percent for substandard uses. Consequently, even a generous, weighted mean for the continent would come up with no less than 40–45percent of all applied nitrogen lost before it reaches the fertilised crops.

Part of the nutrient that is not taken by crops is immobilised *in situ* by the increased mass of soil micro-organisms, but this fixation is only short lived. However, a significant share of the nutrient may be stored for much longer periods (decades to centuries) in long-lived organic compounds that form the soil humus. While it is highly desirable to boost nitrogen content of soils by proper agronomic management, their capacity to store the nutrient is obviously finite, and once a new equilibrium, determined by a complex interplay of many local environmental and management factors, is established the excess nitrogen will have to leave the agro-ecosystem.

Only one route of nitrogen loss is largely, though not completely, innocuous, as denitrification bacteria convert highly reactive nitrates first to nitrites and then to dinitrogen whose basically inert molecules rejoin the enormous atmospheric pool of the gas. The only unwelcome complication of the process is that the reduction does not always proceed entirely to N_2 but stops at nitrous oxide (N_2O) which is a much more efficient absorbers of the outgoing long-wave radiation: its global warming potentials relative to CO_2 is about 60 times higher during the first 20 years after its release.

Volatilisation of ammoniacal compounds and emissions of nitrogen oxides from soils will carry the nutrient downwind to be deposited on other fields as well as on natural ecosystems. Inevitably, emissions of ammonia correlate highly with the intensity of fertilisation and with the density of domestic animals, and atmospheric deposition of ammonia and nitrates is now taking place on such unprecedented scales that nitrogen inputs to natural ecosystems have become significant even by agricultural standards.

Total mean annual deposition of nitrogen averages close to 10 kg N/ha for the entire continent, twice the global mean (van Egmond, Bresser and Bouwman, 2002). Fluxes over the Northwestern Europe are between 20–60 kg N/ha a year, and the peaks, in the Netherlands, are over 80 kg N/ha a year. Annual rates around 60 kg N/ha are as high as average fertiliser applications to North American spring wheat, and they are several times higher than the fertilisation means in most sub-Saharan countries.

During the mid-1990s critical nitrogen loads (that is amounts below which there is no known damage to ecosystems) were somewhat lower than during the mid-1980s, but they were still greatly exceeded in nearly all of Germany, Switzerland, northern Italy, northern France, Belgium and, of course, in the Netherlands (Posch [et al.], 1999). Ecosystem that evolved under the conditions of low nitrogen inputs are particularly affected by these high deposition fluxes. Boreal growth that taken place after the end of the last Ice Age on nitrogen-poor soils, and heathlands are the two ecosystems where even relatively low inputs of atmospheric nitrogen may equal or surpass the quantity of the element made available through net mineralisation of organic matter in the forest floor. As a result, supercritical nitrogen loads will alter species composition by favouring fast growing and nitrofilic plants.

Nitrogen oxides released by soils are eventually converted to nitrates which, together with sulfates, are the major causes of virtually continent-wide acid deposition. Emission of agricultural NO_x are a minor source of the gases compared to the combustion of fossil fuels, but acidification is also intensified by the deposition of ammoniacal compounds once their converted by nitrifying bacteria in soils to nitrates. But by the far the most acute problems with nitrogen leaking from excessively fertilised agro-ecosystems is the leaching of highly soluble nitrates into surface and ground waters.

The best available estimates show that 87 percent of nitrates accumulated in ground waters of the EU countries are leached from agricultural soils; in addition, a substantial share of leaching from non-agricultural lands is also caused indirectly through the nitrification of deposited ammonia which was volatilised from fertilised fields and from the wastes of farm animals. European experience also shows that it may take not merely months, but many years or decades, before leached nitrates reach deep aquifers and before their concentrations, in the absence of de-nitrification, rise to potentially harmful concentrations. Parts of western Europe where heavy nitrogen applications pre-date the WWII provide excellent examples of this gradual process: nitrate concentrations began to rise quickly in both ground waters and surface waters only during the early 1970s.

By the early 1980s nitrates were either near or above the EU's maximum contaminant limit (MCL) of 50 mg NO_3/L in a number of regions, especially in England and the Netherlands. Average concentrations of nitrates in the most affected European rivers – the Thames, Rhine, Meuse, and Elbe – are now two orders of magnitude above the mean of unpolluted streams, and in the early 1990s more than a tenth of western Europe's rivers had NO_3 levels above the MCL. In December 1991 the Council of the European Communities issued its nitrate directive (91/676/EEC) that requires the member states to reduce the nitrate load from the agricultural sector to acceptable levels in all nitrate-sensitive zones and to avoid further pollution from that source. This directive applies not only from nitrogen from inorganic fertilisers but also from manures. The quantities of nutrients applied on individual farms are to be controlled by levies on nutrient surpluses defined by mineral accounting systems and manure disposal contracts (Henkens and van Keulen, 2001).

IX. Summarising the achievement and the challenge

Europe has been at the forefront of the 20th century most important agricultural revolution as the invention of ammonia synthesis from its elements eliminated the most common natural limits on crop productivity. German synthesis of ammonia dominated the pre-WWII global output of nitrogen fertilisers. Europe's post-WWII share of nitrogen fertiliser applications has been falling steadily, but the continent still uses a disproportionate amount of this key nutrient. As a result, average rates of nitrogen applications in several European countries remain among the highest in the world, and they make it possible to harvest the world's highest yields of several staple crops, particularly of wheat.

In spite of higher post-1980 efficiencies of nitrogen uptake, about half of the applied fertiliser still does not get taken up by growing crops, and only a part of this excess can be stored in long-lived soil organic matter. The rest is lost to the environment. The price Europe pays for its obscene surplus of food thus goes beyond the staggering cost of irrationally high agricultural subsidies and the health effects of changing diets. Environmental costs of excess food output are actually more worrisome as many of these impacts would persevere even if the subsidies were to be miraculously cut. Excessive nitrogen in the continent's agro-ecosystems must rank high on any list of such concerns because its impacts range, literally, from high atmosphere (rising N_2O concentrations) to deep wells (nitrate contamination) and include long-term changes of those natural ecosystems that are particularly sensitive to relatively high levels of nitrogen deposition.

X. Agenda for research

Since the mid-1990s human interference in nitrogen cycle has been receiving a great deal of research, as well as public policy, attention, and so in many respects there is now much less uncertainty regarding many basic flows, levels and trends than it was just a decade ago. But, as is always the case with a rapidly advancing research, there is a growing need to integrate this information in an effective and revealing manner. As a part of this effort I would particularly favour preparation of the best possible long-term quantitative summaries of all major trends as well as of all realistic management options that could be used in a variety of environmental and national settings. In addition, attempts to monetise at least the major costs and benefits of the intensive use of nitrogenous fertilisers should be particularly revealing. Such exercises would run into the usual difficulties of quantifying the burdens of environmental and health impacts but they should be of help to policy-makers who need to assess better the cost-benefits ratio of either contemplated actions or of benign neglect.

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