UNDERSTANDING NITROGEN AND ITS USE IN AGRICULTURE
The ability of plants to use simple forms of mineral nitrogen and to transform them into complex proteins is fundamental to animal life on earth. As mankind began to overcome the population-limiting diseases of previous centuries, the major constraint to the growth of population was food, and without the early discovery of a method of fixing nitrogen from the atmosphere there would have been widespread starvation.

This booklet describes the technology and science which underpins the European nitrogen fertilizer industry today, and its provision of a primary plant nutrient which allows the people of Europe to enjoy a plentiful supply of essential food.
Nitrogen was discovered in the early 1770s independently by several physicists and chemists such as the Scotsman Daniel Rutherford, the Englishmen Henry Cavendish and Joseph Priestley, Carl Wilhelm Scheele from Sweden and Antoine Lavoisier from France. In its standard state it is a colourless, odourless and tasteless gas becoming a liquid at -196°C. The chemical symbol for the element, N, is derived from its name nitrogen. The name originates from the Greek words nitron genes meaning nitre-forming and the Latin word nitrum meaning saltpetre, i.e. saltpetre-forming. It is chemically inert in its free state and as such is incapable of supporting life, thus the French word azote (from azotum, without life).

Today there are numerous uses for nitrogenous compounds. The major part is used for mineral fertilizers, but nitrogen is also used in metallurgy for welding, fire fighting, food storage and processing, electronics manufacturing, cooling etc.
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Nitrogen (N) is one of the most widely distributed elements in nature but it rarely forms natural minerals. Therefore, nitrogenous compounds in the soil are not products of weathering processes of the earth crust. Nitrogen is more associated with life than any other (chemical) element. Where there is nitrogen in nature, there is life. Nitrogen is an essential constituent of many compounds found in living cells. All nitrogen in animals and humans is derived originally from plants and microbes because only they have the ability to convert mineral nitrogen into organic nitrogen compounds. Plants take up simple forms of mineral nitrogen from the soil solution, mainly nitrate (NO₃⁻) and also ammonium (NH₄⁺), and assimilate it into more complex organic compounds.

Nitrogen is an essential component of the amino acids which make up proteins in plants, animals and mankind. It is also a critical part of chlorophyll which, powered by the energy from the sun, carries out the fundamental photosynthesis of carbohydrate from carbon dioxide and water and thus supplies animals and man with edible forms of energy.

The photosynthesis by chlorophyll of carbohydrate from carbon dioxide and water.

Nitrogen is also a vital element in the energy-transfer molecules ATP and ADP and is indispensable in peptides, enzymes, hormones and vitamins; it is thus essential in numerous metabolic processes. Furthermore, nitrogen is a constituent of the nucleic acids RNA and DNA that make up the genetic material in all living organisms. It ranks as the fourth most common element in living tissues.

**Introduction**

Nitrogen (N) is one of the most widely distributed elements in nature but it rarely forms natural minerals. Therefore, nitrogenous compounds in the soil are not products of weathering processes of the earth crust. Nitrogen is more associated with life than any other (chemical) element. Where there is nitrogen in nature, there is life. Nitrogen is an essential constituent of many compounds found in living cells. All nitrogen in animals and humans is derived originally from plants and microbes because only they have the ability to convert mineral nitrogen into organic nitrogen compounds. Plants take up simple forms of mineral nitrogen from the soil solution, mainly nitrate (NO₃⁻) and also ammonium (NH₄⁺), and assimilate it into more complex organic compounds.

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**Figure 1:** The essential pathway from nitrogen in the air to human protein: all the nitrogen in man and higher animals has to come originally from plants. The ability of plants to transform mineral nitrogen into proteins is as fundamental to human life as their ability to fix the energy of the sunlight.
Nitrogen in nature.

On earth there are two ‘pools’ of nitrogen with relatively little exchange between them: the gaseous di-nitrogen (N₂) of the atmosphere which makes up about 99% of the total, and the 1% of nitrogen which is chemically bound to other elements. These elements are predominantly carbon (C), hydrogen (H) or oxygen (O) and the compounds formed are part of the biosphere, the hydrosphere and the lithosphere.

Nitrogen makes up slightly more than 78% (by volume) of the atmosphere which is equal to about 86,000 t of nitrogen in the air over each hectare of land. This nitrogen gas cannot be used directly by plants. Due to the strong linkage between the two atoms of di-nitrogen it is almost inert and requires a high energy input to split it into an active form capable of making compounds. Nitrogen from the air is, however, the original source of all nitrogen in compound form and these nitrogen-containing compounds are found in a comparatively thin layer of the biosphere close to the surface of the earth and in the oceans.

Inert atmospheric nitrogen naturally enters the active pool through two processes:

• spontaneously by lightning and photochemical reactions; about 10% of the nitrogen fixed by natural processes is by this route, and
• biologically by specific ‘nitrogen-fixing’ bacteria, such as those associated with leguminous plants or micro-organisms living free in the soil.

As they evolved, some plant species developed a symbiosis with micro-organisms in nodules on their roots. These microbes have enzyme systems that can fix atmospheric nitrogen, which they then make available to the host plant. In return the plant supplies the microbes with assimilates - mostly carbohydrates - from the photosynthesis process which provide the energy necessary to break up the N₂ linkage. To a certain extent the host plant can regulate this flow of assimilates according to its nitrogen needs.

Leguminous crops form nodules on their roots, which contain symbiotic nitrogen-fixing bacteria.
This diversion of some of the carbohydrate produced by these plants limits their harvestable yield and is the reason why leguminous crops like peas and beans yield less than would be expected from their photosynthetic activity. Under optimal conditions a pure stand of clover can fix more than 200 kg of nitrogen per hectare (kg N/ha) in a year.

When leguminous plants die and decay, a substantial part of the nitrogen becomes available for uptake from the soil by other non-legumes.

Free-living nitrogen-fixing microbes compete with other soil organisms for the available decomposable organic matter for their energy supply. As a general average, they may fix up to 2 kg N/ha per year.

Organic matter in the soils and the oceans are the major stores of active nitrogen which have been built up over geological time. This nitrogen is mobile and circulates within and between the different spheres. These cycling processes operate from cellular to global scales and include reaction times from milliseconds to thousands of years. The many factors and processes that are involved in this nitrogen cycling are physico-chemical or biological.

The nitrogen cycle between organisms and their environment comprises the endless natural cycle of growth and decay and represents one of the most important processes and nutrient cycles in terrestrial and aquatic ecosystems.

A nitric oxide molecule formed in the heat of a lightning flash enters the mineral nitrogen pool of the soil, is taken up by a plant, converted to protein which is eaten by an animal and is returned to the soil in the excreta or after the animal dies. Entering the pool of soil mineral nitrogen again, it will be reused by plants and other soil flora and fauna or may be converted by some micro-organisms (those which use nitrate as a source of oxygen) back into di-nitrogen gas and returned to the atmosphere.

\[ \text{Nitrogen cycle in nature.} \]

Figure 2: A simplified nitrogen cycle in nature.
Human activities such as fossil fuel combustion, production and use of mineral fertilizer and the growing of nitrogen-fixing crops have considerably altered the natural nitrogen cycle. The quantity of nitrogen cycling between living organisms, soil, water and atmosphere has increased significantly, largely in relation to increases in the world population.

Today anthropogenic fixation is about 165 mio t of nitrogen, while land-based biological processes fix about 100-140 mio t N annually, i.e. natural fixation processes correspond to some 40-50% of the total nitrogen fixed on land. Marine fixation is estimated to range between 40 and 200 mio t N per year.

**Nitrogen in plants.**

Plants need large quantities of nitrogen, with dry plant material usually containing about 3 to 4% N. Despite its abundance, atmospheric nitrogen is unavailable for plant growth. Most plants can only take up nitrogen from the soil, and then mainly in the two mineral forms: ammonium and nitrate. Although it can be shown in trials that plants grow best on a mixture of nitrate and ammonium in a ratio depending on the crop species, most of the nitrogen is usually taken up as nitrate. Due to the fast microbial conversion of ammonium to nitrate in the soil and to its greater mobility, the roots are more exposed to nitrate than to ammonium. In wet or acid ecosystems this can be different. For example, crops grown under flooded conditions such as paddy rice take up most of their nitrogen in the form of ammonium.

Nitrogen taken up by plant roots is metabolised and translocated to the upper parts of the plant, usually in the form of amino nitrogen (-NH$_2$). In the upper plant most of the amino nitrogen in turn is converted to amino acid and on to proteins. Thus the intensity of nitrogen metabolism and the rate of the protein synthesis control the import of nitrogen by different parts of the plant. Generally, nitrogen in plants is concentrated in the younger parts with the highest growth rates. When the supply of nitrogen from the roots is insufficient, nitrogen from older leaves is mobilised to feed younger plant organs. The protein in these leaves is hydrolysed back to amino acids (proteolysis) which are redistributed to the growing tips and new leaves. The proteolysis in older leaves results in a decline in the chlorophyll content and hence the yellowing which is often symptomatic of nitrogen deficiency.
In green plant material protein-N is by far the largest fraction of the nitrogen-containing compounds, amounting to about 80-85% of the total nitrogen. Many crops (e.g. peas, beans, soya) are cultivated essentially to produce plant proteins for human and animal food. The rate of growth and the protein content of plants are considerably affected by the available nitrogen from the soil and fertilizers.

Other fractions of the nitrogen in plants are the nucleic acids, RNA and DNA, which make up some 10% of total nitrogen and the free amino acids and other amino compounds that account for about 5%.

In plants, nitrogen predominates in functional compounds like enzymes and less in structural components like fibre. Most plants store the energy for the seedling as carbohydrate (starch and fat), but leguminous crops like peas, lentils and beans also accumulate large reserves of proteins in their seeds. Wild leguminous plants have their ecological niche on soils poor in nitrogen because they are not dependent on soil supply. To prevent the seedling from becoming starved of nitrogen before it can develop its own symbiotic system for the fixation of atmospheric nitrogen, the seed protein reserves serve as the early nitrogen source.

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**Figure 3**: The four N-rich component building blocks of the nucleic acid DNA.
Nitrogenous compounds in human and animal nutrition.

The requirement of man and animals is not for protein per se, but for specific amounts of certain amino acids which are the building blocks of the proteins. Animals and humans cannot synthesise the amino group, and in order to build up body proteins they must have a dietary source of amino acids.

Certain amino acids can be produced from others by a process known as transamination, but the carbon framework of a number of amino acids cannot be synthesised in the animal and human body and these are referred to as indispensable or essential amino acids.

Despite the presence of other amino acids, if the essential amino acids are not all present at the same time and in appropriate proportions, human or animal protein cannot be metabolised. Although over 200 amino acids have been isolated from biological materials, only 20 of these are commonly found as components of proteins and of these 9 are essential.

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<tr>
<td></td>
<td>2-5 yr mg/kg/day</td>
<td>10-12 yr mg/kg/day</td>
</tr>
<tr>
<td>Histidine</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Isoleucine</td>
<td>31</td>
<td>28</td>
</tr>
<tr>
<td>Leucine</td>
<td>73</td>
<td>44</td>
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<td>Lysine</td>
<td>64</td>
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<tr>
<td>Methionine and cysteine*</td>
<td>27</td>
<td>22</td>
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<tr>
<td>Phenylalanine &amp; tyrosine</td>
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<td>22</td>
</tr>
<tr>
<td>Threonine</td>
<td>37</td>
<td>28</td>
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<tr>
<td>Tryptophan</td>
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<td>3</td>
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<td>Valine</td>
<td>38</td>
<td>25</td>
</tr>
<tr>
<td>Total (excl. histidine)</td>
<td>352</td>
<td>216</td>
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* Sulphur-containing amino acids.

Table A: FAO/WHO/UNU (1985) estimates of essential amino acid requirements in pre-school and school-aged children and in adults.
Humans and animals obtain the nitrogenous compounds they need for metabolism, growth and reproduction by eating the protein in food from plants and animals. Dietary proteins are needed throughout life but are required in relatively large amounts by growing infants and young and highly productive animals. The relative need declines fast with maturity and the daily requirement of protein for normal adults is around 0.8 grams per kilogram of body weight, which is about 10 g of nitrogen for a person of 75 kg body weight.

Proteins are complex organic compounds of high molecular weight and are found in all living cells, where they are intimately connected with all the phases of activity that constitute the life of the cell. Cell walls of animal and human cells are composed almost entirely of lipids and proteins. In plants, animals and man, proteins are the main nitrogen-containing compounds. In animals and humans, muscle, skin, hair, nails (feathers and wool) consists mainly of protein, which on average contains 16% nitrogen in the dry weight. The total human body contains around 2.6% N, i.e. an individual weighing 75 kg contains almost 2 kg of nitrogen.

Figure 4: Two simple amino acids out of 20 which commonly form proteins.
The agricultural nitrogen cycle.

Human activities are greatly increasing the amount of nitrogen cycling between the living world and the soil, water and atmosphere. From the cycling perspective, soils are the most concentrated and active reservoir of nitrogen in the lithosphere. Around the world, the total nitrogen content of cultivated soils varies from 0.02 to 0.4%. In Europe the common range is 0.04 to 0.2% N which is equivalent to 1,800 to 9,000 kg N/ha in the ploughed layer of 30 cm depth. This nitrogen is mostly bound in organic material and is therefore not in the soil solution nor quickly available to growing plants. Soils with low nitrogen reserves are considered infertile and are difficult to farm economically. When the soil nitrogen content is above the normal range there is an increased risk that the crop will not recover some of the extra available nitrogen.

Agriculture is part of the overall natural nitrogen cycle. It is based on natural processes and with the development of modern productive agriculture to satisfy the increasing demand for food, the cycle has had to become influenced by man.

The soil nitrogen and also the applied fertilizer nitrogen - from mineral or organic sources - is transformed between different forms by the same complex processes or reactions. It is important to understand that increased fertilizer inputs to agricultural soils have not created new pathways within the nitrogen cycle but they have rather increased the amount of nitrogen within some compartments and the flow of nitrogen between them; in some cases these increases are in compartments and flows which are unavailable for agricultural use and are therefore referred to as 'losses' (see pages 39 to 46).

**Figure 5**: The global nitrogen cycle.
Agriculturally the additional quantity of nitrogen in the cycle originates from increased turnover of organic matter in the soil due to changes in agricultural systems and from external nitrogen sources. Permanent grassland and prairies were ploughed by settlers and the area of arable land for cropping increased in most parts of the world. In more modern times the increased production of nitrogen-fixing leguminous crops as well as the industrial fixation of nitrogen for the manufacture of mineral fertilizers have added more nitrogen to the agricultural nitrogen cycle (see pages 18 to 28).

The principal forms of nitrogen in soil are the nitrogen bound up in organic compounds in the humus and the ‘mineral’ forms ammonium (NH$_4^+$) and nitrate (NO$_3^-$). Nitrate and ammonium are both directly available to plants, but most of the nitrogen is taken up as nitrate. While ammonium nitrogen is adsorbed onto the clay particles, nitrate is freely dissolved in the soil solution. Thereby nitrate is ‘delivered’ to the root with the water the plant takes up while the root has to collect the ammonium at the sorption site.

Nitrogen inorganicisation.
Nitrogen in organic soil compounds is quite immobile and unavailable to plants. It has been estimated that 1 to 3% of total organic nitrogen in temperate zone soils is mineralised by micro-organisms in a single year, resulting in a theoretical complete turnover of soil nitrogen every 30 to 70 years. The conversion of organic nitrogen to the ammonium ion is known as ‘mineralisation’.

Nitrification.
Ammonium can be utilised directly by plants but the major part is converted in two steps to nitrate by a group of bacteria. This oxidation process, known as ‘nitrification’, can be delayed by certain chemicals that specifically affect (inhibit) the activities of Nitrosomonas (see page 37, stabilised fertilizers).

Denitrification.
In the ‘denitrification’ process nitrate is reduced to di-nitrogen gas (N$_2$) under anaerobic conditions. However, as an intermediate product nitrous oxide gas (N$_2$O) is formed and this can also be emitted to the atmosphere. The extent of this denitrification depends on climatic and soil conditions and will be discussed on page 42 (nitrous oxide emissions).
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Box 1

**Bioconversion processes in soil**

**Mineralisation:**
A wide range of micro-organisms in the soil breaks down organic material to supply the energy they need for life. During this process plant nutrients, e.g. phosphorus, potassium and nitrogen, are also released. Organically bound nitrogen is transformed first to imino-N and then to ammonium-N. Fresh organic matter such as plant residues are decomposed (mineralised) almost entirely within a few months during summer, while 10-20% of fermented material like farmyard manure or compost is decomposed annually. The soil humus consists of very stable molecules which are only built up or mineralised over long periods.

**Immobilisation:**
Micro-organisms feeding on the organic soil material incorporate building blocks like amino acids and mineralised nutrients into their bodies as they grow and multiply. This microbial population can thus fix mineral ammonium- or nitrate-N from the soil solution rendering it temporarily unavailable to plants. This occurs particularly when easily degradable organic material low in nitrogen, e.g. straw, is abundant in warm humid weather. Under such conditions up to 100 kg of nitrogen per hectare can be immobilised temporarily.

**Nitrification:**
Some specialised bacteria profit from the energy bound in ammonium-N by oxidising it in two steps into nitrate. *Nitrobacter* spp. transform ammonium to nitrite and *Nitrosomonas* spp. convert nitrite to nitrate. Under aerobic conditions, almost all of the ammonium becoming available in the soil will be nitrified to nitrate.

**Denitrification:**
When oxygen is limiting in flooded or waterlogged soils some microbes have the ability to use the oxygen from nitrate for their metabolism by reducing it to NO, N₂O or N₂. These gaseous losses to the atmosphere can reach 20 to 30 kg N per hectare annually. The rates of all these microbial activities in the soil depend on several environmental factors such as water content, oxygen supply, soil-pH and temperature. Microbes are most active in warm humid soils up to about 35°C. These processes effectively cease at temperatures below about 5°C and in dry soils.

The mineralisation increases the pool (amount) of plant-available nitrogen as ammonium and nitrate in the soil. However, conversely, microbes also consume mineral nitrogen, mainly ammonium-N but also nitrate-N, and convert it by binding it into organic substances. In this respect a general rule is valid. If the carbon:nitrogen (C:N) ratio in the soil is higher than 20:1 this 'immobilisation' is favoured, so mineral nitrogen is transformed to organic nitrogen. If the ratio is below 15:1 mineralisation dominates and as a consequence the so-formed ammonium and its oxidation product nitrate can be taken up by plants. Because humus, the long-term form of soil organic matter, has a fairly constant C:N ratio of about 10:1 arable soils in most parts of Europe have a C:N ratio of between 8:1 and 15:1.

Ammonium and nitrate supplied from mineral fertilizers are subject to the same microbial processes in the soil.
The organic matter content of a soil and the C:N ratio of the organic matter are specific for a site and its use; they depend on natural factors like climate, water regime and soil type, on the type of vegetation or system of use, (forest, prairie, arable land or grassland), and the intensity of use (frequency of working the soil, species of crops grown, input/output of plant nutrients and organic matter). If every factor remains constant a soil organic matter content with a C:N ratio which is typical for this situation will establish after decades.

The results of the Broadbalk Continuous Wheat Experiment at Rothamsted in the UK show that the total nitrogen in the 0 - 23 cm soil layer rose from 2,900 to 3,600 kg N/ha when fertilised over 137 years with 144 kg N/ha compared to the control which received no fertilizer. The organic matter (C) level and its associated nitrogen content stabilised on this clay soil after about 30-40 years for both the fertilised and unfertilised plots, and has subsequently changed little. The carbon and nitrogen equilibria were lower in the unfertilised plots but the C:N ratio remained similar for all treatments on this site.

A section through the soil shows the ploughed layer enriched with organic matter, with some enrichment (for example by earthworms) of the upper part of the subsoil and the associated mineral subsoil.
Nitrogen and the world food supply.

Manufactured nitrogen fertilizer is now an essential requirement for the sustainable life of the world’s population. It is the basis for the production of almost 50% of the food consumed by mankind. In 1996 a world population of 5.75 billion people consumed about 25 mio t N with their meals (Figure 7). The protein available globally is more than sufficient for the absolute needs of mankind, but this is not to say that all the world’s population is well fed.

The difficulty associated with the management of this nitrogen and its presence in the natural environment is the challenge man has to face for the availability of food. Further development of scientific and technical expertise will increase the efficiency in the production and use of fertilizer nitrogen to ensure the continuing supply of food alongside the necessary protection of the world environment.

Figure 7: Nitrogen in the global food and feed harvest of the mid-1990s (all values are in mio t N/year). from Smil, 1999
"Long-Range Perspectives on Inorganic Fertilizers in Global Agriculture"

I have prepared a detailed account of nitrogen flows in global agriculture, which shows that during the mid-1990s about 85% of all nitrogen in food proteins available for human consumption (21 out of 24.5 mio t N) came directly in plant foods or indirectly via animal products from the world's cropland; the rest comes from pastures and from aquatic foods (Figure 7) (Smil, 1999). Because synthetic nitrogen fertilizers provided about half of the nutrient in harvested crops (the most likely range of my calculations is 44%-51%), roughly 40% (37%-43%) of the world's dietary protein supply in the mid-1990s originated in the Haber-Bosch\(^1\) synthesis of ammonia.

Low-income countries now consume about two-thirds of the world's nitrogen fertilizers, which provided about 55% of the total nutrient supply reaching their fields. Because no less than 92% of their food proteins were derived from crops, inorganic fertilisers supplied at least half of all nitrogen in their diets. This would be an equivalent of feeding no less than 2.2 billion people or roughly 40% of the world's 1996 total population: these people now depend on the Haber-Bosch synthesis for what is, on the average, a barely sufficient supply of their basic food needs, that is, for their very survival.

Another estimate of our dependence on ammonia synthesis can be obtained by an entirely different approach - by calculating the population totals supportable by specified diets. In 1900 the virtually fertiliser-free agriculture was able to sustain 1.625 billion people by a combination of extensive cultivation and organic farming on the total of about 850 mio ha. The same combination of agronomic practices extended to today's 1.5 billion ha of cropland would feed about 2.9 billion people or about 3.2 billion when adding the food derived from grazing and fisheries. This means that without nitrogen fertilisers no more than 53% of today's population could be fed at a generally inadequate per capita level of 1900 diets. If we were to provide today's average per capita food supply with the 1900 level of agricultural productivity, we could feed only about 2.4 billion people or just 40% of today's total.

Abstract from by Prof. Vaclav Smil, University of Manitoba, Canada.

\(^1\) (see pages 22 to 24)
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Nitrogen sources in agriculture

Traditional nutrient sources.

About 10,000 years ago our ancestors, the hunter-gatherers, started to supplement their food supply by actually growing as crops those plants from which they had so far only collected the edible parts. They must have soon realised that not all sites were equally productive. Besides visible features like soil structure and moisture content other less obvious inherent parameters influence the fertility of a soil. The nutrient content for example could only be judged by the richness of the natural vegetation. So the early farmers must soon have learned to select their field plots carefully.

What will have taken much longer to realise, since it would only become noticeable after several years or even generations, was that even on the most fertile soils the yield tended to decline after years of continuous cultivation. The reason was a constant removal of plant nutrients from the soil with the harvest. It is reported that in the fertile basin of Mesopotamia the wheat yield dropped from 2 t/ha to 0.8 t/ha over a period of 300 years of cultivation.

Continuous farming developed along two principles: either by

- shifting cultivation, in which fields were abandoned after some years of cultivation and virgin land occupied instead, or by
- farming in the valleys of rivers where major annual floods deposited nutrient-rich sediments to replace the nutrients removed with the harvest.

In different regions man developed systems that most suited local conditions. Northern European agriculture started in the Middle Ages with the two-course rotation inherited from the Romans: one year of autumn-sown wheat, barley or rye and one year of fallow. This not only halved the stress put on the reserves of plant-available nutrients in the soil, but during the second year additional nutrients became available by the break down of organic and mineral soil particles.

Since Greek and Roman times it was known that the application of lime, dung or other organic material would increase the yield of crops. Therefore, the dung from the stables was taken to the arable land and the pen in which the animals were kept overnight was preferably built on the fallow land. Litter collected from the forest and hay made on remote meadows also contributed plant nutrients into the arable system. But this was only a horizontal nutrient movement which impoverished other natural ecosystems for the benefit of those fields in which man wanted to grow cereals for food.

A specialised agriculture developed early in the Nile valley, where annual flooding renewed the soil fertility.
As the population grew, it was no longer feasible to have half of the cleared land in fallow. In the 8th century a three-course rotation was promoted. It introduced one year of spring crops between the traditional winter cereals and the fallow. Less demanding species like oats, or buckwheat were grown or nitrogen-fixing leguminous crops like peas and Vicia beans in the north or lentils and chickpeas in the south of Europe were chosen. While the legumes left some residual nitrogen for succeeding crops, their small share could not really improve the nutrient status of the soil. But the overall harvest, now from two thirds of the cleared land, was higher. However the three-course rotation accelerated the nutrient depletion of soils.

Over the centuries an ever-increasing population demanded more food. Clearing additional forest and draining the wetlands left less natural ecosystem to supply external plant nutrients, but created a greater arable area depending on them. This could be partly compensated for by improved methods of working the soil. A better and animal-drawn plough opened up a larger soil volume thus providing more plant nutrients to the roots. All other available sources of nutrients were used such as mud sediments from lakes and rivers or the thin fertile upper layer of soil taken in sods from heathland. However, this only allowed the average wheat yield to be maintained at 0.8 t/ha. An additional problem was that all these external sources contained only small quantities of nutrients so that large volumes had to be moved to the field to really improve the fertility, and transport was very laborious at that time.

During the 18th century the net supply of nitrogen was improved by growing leguminous fodder crops or clover grass mixtures on the fallowed land. This not only increased the residual nitrogen left in the soil by the root system of the legumes but also resulted in more farm-yard manure which was also richer in nitrogen. As the nitrogen supply was partly improved, other nutrients, particularly phosphorus and potassium, became limiting. So the growth of the nitrogen-fixing clover and lucerne was hampered by the availability of phosphate.
The intermediate step.

Up to the beginning of the 19th century farmers had developed three ways to channel plant nutrients to the arable land to help to maintain its fertility:

- recycling as much as possible of the nutrients originally taken up by the crops from the arable soils as farm-yard manure and crushed animal bones,
- adding nutrients to the manure by using roughage and litter collected from meadows and forests, but thus impoverishing other natural ecosystems,
- fixing additional nitrogen from the air by growing leguminous crops as part of the rotation.

While together it might have been enough to stabilise yields, it would never have been sufficient to increase yields to the extent that the continuing growth of the population demanded. The vast majority of the suitable land in Europe had already been cleared so that further growth of the arable area was limited. An increase in yields could only be achieved when the nutrient concentration in the soil was raised enabling the plants to take up more in the limited time of their growing season.

In the first decades of the 19th century, more nutrients from outside the farming systems became available in the form of mineral fertilizers. Gas lighting was installed in the major cities using coke-oven gas as feedstock. Coke-oven gas contains 0.7 to 1.5% ammonia which was precipitated as sulphate of ammonia (21% N). While the supply of this source of nitrogen was limited by the amount of gas produced, a second product with no such limitations became available. Initially for use in gunpowder, the production of sodium nitrate started in 1804 in the Atacama desert of Chile, Peru and Bolivia. This salt was leached out of a soil layer naturally rich in nitrogen (1 - 5% N) by hot water, purified and dried. This energy- and water-consuming process was expensive to carry out in a desert and the product remained costly until after the nitrate war (1879-1884) when foreign investment in the mines, now completely on Chilean territory, rationalised the production. While in 1830 only 850 t of Chilean nitrate (15 - 16% N) had been exported it had risen to more than 1 mio t (160,000 t N) by 1890. The peak was reached around 1930 at about 3 mio t annually.

The demand for nitrogen fertilizer was also supplied by another product of natural origin called ‘Guano’. Based on the knowledge of Peruvian Indians, the droppings of sea birds which had accumulated under extremely dry conditions on small islands off the Peruvian coast had been successfully tried as a fertilizer in Europe. Beginning in about 1840, guano (14% N, 14% P₂O₅) was imported into Europe in such quantities that the deposits were exhausted by 1875, although some of them had been up to 60 m deep. Guano was the common load for a ship coming back from the pacific coast of South America. In only 35 years they hauled 16 mio t to Europe. This is equal to 64,000 t of nitrogen annually.

Sailing ships hauled millions of tonnes of guano and Chilean nitrate around Cape Horn to fertilize European fields, such as the Pamir shown here.
The technical age.

After the rapid depletion of the guano deposits, European agriculture was dependent entirely on by-product sulphate of ammonia and Chilean nitrate as external sources of nitrogen. So it is understandable that in 1898 the English chemist Sir William Crookes, in a widely published lecture, called on all chemists to find a way to fix nitrogen chemically from the unlimited reserves in the air. He said that without a new source of nitrogen fertilizer famine would be inevitable within two to three decades.

In 1895 Adolf Frank and Nikodemus Caro found in their experiments that at 1,000 to 1,100°C calcium carbide combines with nitrogen from the air to form calcium cyanamide. When calcium chloride was added, the temperature could be lowered to 300°C. The first commercial plant with an annual capacity of 4,000 t N was built in 1905 in Italy followed by two plants in Germany in 1907 (4,200 t N per year) and 1908 (6,300 t N per year). The economy of calcium cyanamide production depended on cheap energy, thus two plants were powered with hydroelectricity and the third with local lignite.

The natural phenomenon, in which the heat generated by lightning causes the di-nitrogen (N2) in the air to be oxidised to form nitric oxide (NO) had been well understood since the 18th century. In 1903 the Norwegian technicians Kristian Birkeland and Samuel Eyde used powerful electro-magnets to deform an electric arc to a two dimensional disc-shaped flame produced crosswise in a stream of air. After passing through the 3,500°C flame the air contained 1.5 - 2.0% NO which was precipitated in water to give nitric acid, this being neutralised with calcium carbonate. Although between 50 and 75 kWh were needed per kg of nitrogen this process was economic when based on hydroelectricity.
In 1913 three plants were operating in Norway producing a total of 70,000 t of ‘Norge’ nitrate containing about 12,000 t of fixed nitrogen, equivalent to about 3% of the nitrogen exported in Chilean nitrate in the same year.

The limitation of both the Birkeland/Eyde and the Frank/Caro process was their dependence on cheap electricity and the limited scope for further improving their efficiency. Chemists in several countries therefore went on to look for alternatives. One of them was Fritz Haber, professor of chemistry at the University of Karlsruhe in Germany. Starting from the known disintegration of ammonia into its components, hydrogen and nitrogen, at high temperature, he successfully reversed the process and synthesised ammonia from the two elements in 1904. But the yield was so low, that he gave up. However with better understanding of the principles of thermo-dynamics he started again in 1908, varying temperature and pressure in the converter pipe. Using an osmium catalyst at 175 - 200 atmospheres pressure and 550 - 600°C, about 6% of the gas mixture was transformed into ammonia. After extreme cooling he removed the liquefied ammonia and recycled the non-converted mixture of hydrogen and nitrogen. This process was patented in 1908.

For further development Haber contacted ‘Badische Anilin und Soda-Fabrik’ (BASF) at Ludwigshafen, Germany. BASF assigned Carl Bosch, a young chemist with metallurgical experience, to the project. His task was to scale up the tiny equipment used by Haber to a pilot plant and further to a commercial plant. At the same time Alwin Mittasch started screening thousands of different catalysts to further improve the rate of conversion.

When Bosch tried to build a somewhat larger converter, even the strongest tube the German steel industry could supply burst after a few hours of operation. He discovered that hydrogen molecules penetrated into the steel and destroyed its structure so that it became brittle.
The problems Bosch was facing seemed insurmountable, but a solution was found by using a double-walled converter tube. This was made by combining a soft iron inner liner unaffected by hydrogen with an outer steel jacket with small holes which offered the penetrating hydrogen an easy escape. In 1913 a pilot plant produced about 0.4 t of ammonia per day and the first commercial plant with a capacity of 7,200 t N per year came on stream the same year in Oppau close to Ludwigshafen. The capacity was continuously increased.

In 1917, a second plant with a capacity of 36,000 t N per year started in Leuna (near Halle, Germany), where local lignite was used as feedstock. It was decided to increase the capacity to 130,000 t N per year while the first part was still under construction. Such scaling up was possible since in its important parts the plant consisted of several parallel lines to which additional lines could be added. Only in the 1960s could the necessary components be built at a size which allowed the construction of a single-line plant. While 1,000 - 1,500 t per day NH₃ plants were a typical size in the 1970s, plants with more than 3,000 t NH₃ per day capacity are under construction now.

<table>
<thead>
<tr>
<th>Year</th>
<th>t/d NH₃</th>
</tr>
</thead>
<tbody>
<tr>
<td>1913</td>
<td>3 - 4</td>
</tr>
<tr>
<td>1915</td>
<td>85</td>
</tr>
<tr>
<td>1955</td>
<td>200</td>
</tr>
<tr>
<td>1970</td>
<td>1200</td>
</tr>
<tr>
<td>1990</td>
<td>2000</td>
</tr>
<tr>
<td>2005</td>
<td>3300</td>
</tr>
</tbody>
</table>

Table B: Typical capacity of a single ammonia reformer.

Advances of the Haber-Bosch process.

Technical:
- change from batch to continuous flow.
- knowledge-based process control.
- change from parallel streams to one single line.
- better catalysts (composition, shape, quantity).
- improved energy efficiency (use of surplus heat, optimising temperature and pressure).

Feedstock:
- coal.
- gases (natural, refinery).
- naphtha.
The design of the process equipment, the energy management in the plant and the catalyst have all been improved considerably over the years. Nitrogen was always taken from the air but the source of hydrogen changed over time. The process started with coal as feedstock for the production of water gas by reacting glowing coal with water vapour, but carbohydrates such as naphtha and natural gas are the preferred feedstocks today. The energy requirement decreased from about 100 MJ/kg NH₃ in 1913 to 27 MJ/kg NH₃ today, which is close to the theoretical minimum of 25 MJ/kg.

The remarkable progress in technical and chemical knowledge made the continual increases in efficiency possible. Today 99% of the industrially fixed nitrogen is produced using the Haber-Bosch process. Both the inventors were honoured with a Nobel prize, Haber in 1918 and Bosch in 1931.

Natural gas | 71.1 %
Naphtha, LPG, refinery gases | 5.6 %
Fuel oil, liquid residues | 3.7 %
Coke, coal, coke oven gas | 19.0 %
Others | 0.6 %

Table E: World nitrogen production according to process (1000 t N) (other by-product nitrogen originally derived from the Haber-Bosch synthesis, is included under “synthetic ammonia”), from Smil (2001).
Organic fertilizer sources.

Animal manures and slurries are the principal organic fertilizers and have varying nutritional values. Significant proportions of the nutrients in them are recycled within agriculture. Their contribution to plant growth is highest in the year of application but is still measurable for several cropping seasons. On a farm, the available quantities of manure and slurry are allocated to the fields before other nutrients are considered. If the nutrient needs of the crops in these fields cannot be satisfied from the organic fertilizers then mineral fertilizers are used to supply the balance.

In addition to manures and crop residues available on farm, which have always been used as nutrient sources in agriculture, there is a further supply of organic materials. They comprise a range of so-called bio-wastes including urban wastes (e.g. sewage sludge, biological and green waste) and industrial wastes (e.g. food processing waste, paper mill sludge).

Together, these non-farm wastes can be referred to as ‘Exogenous Organic Matter’, meaning that they are derived externally from the agricultural context in which they are often used.

Figure 8: In the EU-15 the majority (86%) of all organic waste materials are generated and used on farm, with 7% of the balance coming from industrial and 7% from urban wastes.
Due to their relatively low nutrient contents a main intention of the incorporation of sewage sludge and other exogenous wastes into the soil is to build up organic matter and potentially improve soil structure. Bio-waste compost is an organic amendment which can act as a soil improver because of its high content of stabilised organic matter although it has only a modest fertilizing value.

Many of these products are not really needed by agriculture. Under best farming practice the organic matter content in the soil of a specific site can be maintained without exogenous inputs. They contribute very little positively, and may have associated disadvantages, for example from non-nutrient contamination and because of the energy needed to spread and incorporate them, relative to their agricultural value.

It is not easy to be precise in the use of organic waste materials in the field, for example it is difficult to achieve a uniform spread pattern and application rate. Furthermore nutrient release is difficult to assess, predict and control, all of which are requirements for the use of fertilizer in modern agriculture.

Slurries and manures, estimated at more than 900 mio t in the EU-15, are practically all applied to agricultural land (56% in the form of slurries). They represent up to 86% of total weight and 90% of the nitrogen from organic waste materials spread onto the land, with the balance being from sewage sludge and industrial wastes.

Farmyard manure contains the plant nutrients in the indigestible parts of animal feeds and straw, but 20-30% of the nitrogen is lost during fermentation and storage.
Livestock manure and slurries.

Manures and slurries contain in total an estimated 6.4 mio t of nitrogen, being produced each year by the 1.4 billion farm animals in the EU-15.

The term ‘livestock manure’ covers a wide range of nutrient sources with different physical properties and nutrient contents. Furthermore, the nutrient contents of manures vary regionally and depend on the type of livestock and the management system (Table F).

<table>
<thead>
<tr>
<th>Source</th>
<th>Total N (g/kg DM*)</th>
<th>N-NH₄⁺ % of total N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cattle manure</td>
<td>12.6 - 28.6</td>
<td>10%</td>
</tr>
<tr>
<td>Pig manure</td>
<td>21.9 - 32.7</td>
<td>10%</td>
</tr>
<tr>
<td>Poultry manure</td>
<td>28.6 - 45.7</td>
<td>70%</td>
</tr>
<tr>
<td>Cattle slurries</td>
<td>31.4 - 47.3</td>
<td>25 - 78%</td>
</tr>
<tr>
<td>Pig slurries</td>
<td>55.0 - 103.2</td>
<td>56 - 65%</td>
</tr>
<tr>
<td>Poultry slurries</td>
<td>28.2 - 74.1</td>
<td>21 - 70%</td>
</tr>
<tr>
<td>Cereal straw</td>
<td>5 - 13</td>
<td></td>
</tr>
</tbody>
</table>

Table F: Indicative nitrogen content of various organic sources generated on-farm (Leclerc, 2001).

Due to the mineral nitrogen content being mostly in the NH₄⁺ form, nitrogen from slurries is subject to loss through volatilisation as ammonia (see page 42), which is one of the reasons why nitrogen from organic fertilizers cannot be used as efficiently as mineral fertilizer nitrogen. Of the total amount of nitrogen in animal slurry and manure produced only 4.1 mio t N are estimated to be actually available to crops.

Generally, nitrogen contained in livestock manures must be transformed by bio-chemical processes (mineralisation and nitrification) before becoming available for plant nutrition (see page 14). However, any organic nitrogen which is mineralised later in the year after the period of active uptake by the crop may be leached from the soil during winter and can contribute to pollution of ground water (see pages 39 and 40).
Sewage sludge and bio-wastes.

In the year 2000 the total generation of sewage sludge from urban waste water treatment plants in EU-15 was about 112 mio t but this contained only 7.2 mio t of dry matter. Approximately 40% is applied to agricultural land, the rest is mainly sent to land-fill (50%) or incinerated (10%) in varying proportions in the different Member States of the EU. In addition, almost 180 mio t of solid waste is produced by municipalities of which 30% is potentially biodegradable with a theoretical compost production of up to 20-25 mio t of compost.

However, the application of bio-wastes on soils may have certain undesirable environmental consequences arising from its misuse (such as inappropriate dose rates or timing of application) or its low quality related to the presence of contaminants such as heavy metals (Cu, Zn, Cd and Pb), organic compounds (such as dioxins, furanes) and pathogens (e.g. Salmonella, Enterobacteriaceae).

A substantial part of the organic matter of sewage sludge is mineralised within a few weeks. Therefore it should only be spread onto the land shortly before sowing the crop which is to use this mineralised nitrogen. This is sometimes difficult to achieve, since sludge also must be ploughed in before sowing to avoid direct contact with the growing crop.

For reasons of hygiene exogenous organic matter may not be applied to several food crops nor onto grassland.
MINERAL NITROGEN FERTILIZERS

A mature industry.

The use of nitrogen fertilizers in west Europe increased significantly from the 1950s to early 1980s as agricultural output expanded, with slight falls in 1973 and in 1982 corresponding to the first and second global oil crises (Figure 9).

However, the consumption of nitrogen fertilizers started to decline in the middle of the 1980s with a major decrease occurring in the early 1990s due to the reform of the European Union Common Agricultural Policy (CAP) and the introduction of ‘set aside’.

Since then, between 1992 and 1998, the west European consumption of fertilizers increased slightly, though never reaching the historic high level of 1986.

A nitrogen fertilizer factory needs access to an economic gas supply and efficient transport links.
The decline in fertilizer use in Europe overall was also significantly affected by reductions during the economic transition in central Europe and the Former Soviet Union (FSU).

During this period, fertilizer consumption increased faster in the rest of the world than in west Europe, due to differences in the stage of agricultural development and regulation (such as the EU Nitrates Directive and nutrient budgeting) between west Europe and other countries. By 1996, world nitrogen consumption had recovered to its 1989 level, increases in developing countries having offset falls in west Europe and the FSU.

In 2001, with 9.39 mio t N, west Europe accounts for 11% of world consumption. In the future this fertilizer consumption is expected to decline and stabilise after 2006 to reach 9.2 mio t by 2010.

The trends of fertilizer consumption in EU countries will be influenced by a number of factors, including:

- CAP measures directly or indirectly influencing the output of agricultural products e.g. fixing of base area, compulsory and voluntary set aside, production quotas, prohibition of the ploughing of permanent grassland, extent of support for non-food crops.
- Agri-environmental measures punishing or rewarding certain practices e.g. the Nitrates Directive, Flora and Fauna Habitat Directive, support for organic farming, and the implementation of such measures (e.g. Cross Compliance).
- Technical progress leading to increasing yields and nutrient efficiency, e.g. in plant breeding, crop husbandry and precision agriculture.
- Developments of the relative prices of fertilizers and agricultural products, thereby changing the cost-benefit ratio for mineral fertilizer use.

This pressure will further decrease the western European share of world nitrogen consumption, whereas, according to the FAO, developed countries will generally see an increase in nitrogen use to 2030, at an annual rate of 0.7% to 1.3% per year.

From 2000 to 2004, in response to the decrease in fertilizer consumption, the West European fertilizer industry reduced its nitrogen capacities by some 2 mio t N (Figure 10). Recent studies forecast a further decrease of 2 mio t by 2012.
97% of nitrogen fertilizer is derived from ammonia, the production of which is highly dependent on the supply of natural gas. As a consequence, the world fertilizer industry develops new capacities

• where cheap natural gas is available (as in the Near East and the Caribbean);
• in high-demand developing countries (such as South Asia and China); and
• where the social and environmental legislation is less constraining than in other countries.

In only twelve years’ time the west European share of the global ammonia capacity decreased from 13% to 9% between 1988 and 2000. At the same time, the fertilizer industry has focussed on two aims:

• relating to the importance of the cost and use of energy, the first aim has been to focus research towards low energy processes in order to increase efficiency in nitrogen production, as well as in the agricultural use of nitrogen;
• relating to the ‘sustainable development’ approach of developed countries, the second aim has been focussed on investment designed to reduce environmental and social impacts. EFMA’s Environment Policy is based on the guiding principles of the Responsible Care programme. This programme is based on:
  - promoting safety and protecting the health of workers,
  - minimising the environmental impact of production sites,
  - reducing major industrial risk,
  - safeguarding natural resources,
  - supporting the improvement in fertilizer practice and use, and disseminating the principles of Good Agricultural Practice (GAP).

Nitrogenous fertilizers are applied during only five months of the year. Large quantities need to be stored to satisfy this demand during the season.
Types of nitrogen fertilizer.

Farmers in western Europe have always had access to a full range of fertilizer types. The current usage of a variety of products has been the result of experimental and practical experience of using the different nitrogen sources on the range of crops and soils in different European climatic conditions.

In western Europe a relatively balanced range of nitrogen fertilizers is used, but since the 1970s most of the increase in world consumption of nitrogen has been as urea. In developing countries the higher nitrogen concentration in urea can reduce distribution, storage and handling costs per unit of nutrient, although this apparently much higher nitrogen content is far less significant if it is measured on a volumetric basis (see Table G). In the case of developing countries the urea share now represents 67% of total nitrogen consumption compared with only 16% in the western Europe.

Table G: Comparisons between the % w/w and % w/vol N contents of major fertilizers.

The dominance of the use of urea in the developing countries may be more due to logistics and economics than to agronomic suitability and consideration of environmental impact. The potential for loss of ammonia from urea when used inappropriately can be significant, and is generally larger and more difficult to manage than losses from nitrate-based sources (see page 42).
Principal straight nitrogen fertilizers used in western Europe:

- **Calcium ammonium nitrate** (CAN) is a mixture of ammonium nitrate and a minimum of 20% calcium/magnesium carbonate. Its nitrogen concentration ranges from 25% to 28%. With a share of 30% it is the main source of straight nitrogen in western Europe. Half of the nitrogen is in the nitrate form, which is immediately available to plants, and the other half is in the ammonium form. Ammonium nitrate based fertilizers are well suited for most European soils, crops and climatic conditions.

- **Ammonium nitrate** (AN) is another concentrated source of nitrogen (33.5% to 34.5% w/w). It accounts for 21% of total fertilizer nitrogen in western Europe. It is the most commonly used straight nitrogen fertilizer in France (38%) and in the UK (68%) where it holds the place CAN has in other countries.

- **Urea** is the most concentrated solid nitrogen fertilizer (46% w/w). The availability of nitrogen for plant uptake can be delayed, particularly in cold spring weather, because urea must be transformed into ammonium and to the final nitrate form. This chemical transformation is dependant on temperature, and in western Europe the use of urea is traditionally strong in areas bordering on the Mediterranean Sea.

- **Liquid solutions** represent 12% of total nitrogen consumption in western Europe. The most typical formulation is made using 50% urea and 50% ammonium nitrate in water (urea/ammonium nitrate, UAN) to form a fully dissolved clear liquid fertilizer (28-32% N). UAN offers farmers the advantage of reduced manual handling but it requires special storage facilities and equipment for transport.

The type of particle depends on the production process: granular ammonium nitrate, prilled NPK and crystalline calcium nitrate need different settings for the spreader.

Fertilizer must be free flowing to assure easy handling and uniform spreading.
Other straight nitrogen fertilizers:

- **Ammonium sulphate** has a relatively low nitrogen content (21%, all in the ammonium form). It also, however, contains 24% sulphur (S), another essential plant nutrient.
- **Ammonium sulphate nitrate** is a combination of ammonium sulphate and ammonium nitrate (typical grade: 26% N, containing 7.5% as nitrate, 18.5% as ammonium, with 14% S.)
- **Calcium nitrate**, which contains 14.4% N in nitrate form and 19% water-soluble calcium, is a form of nitrogen particularly suited for fast growing market-garden crops and for fruit trees due to its quick action.
- **Sodium nitrate, Chilean nitrate and calcium cyanamide** are used in small volumes on special crops.
- **Anhydrous ammonia** (82% N) is applied by injection into the soil and represents less than 1% of total nitrogen fertilizer used in western Europe.

### Table H: Nitrogen content of the main nitrogen fertilizers in western Europe (year 2001/2002).

<table>
<thead>
<tr>
<th></th>
<th>N content (% w/w)</th>
<th>Consumption (ktN)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Straight nitrogen</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anhydrous ammonia</td>
<td>82</td>
<td>78</td>
</tr>
<tr>
<td>Urea</td>
<td>46</td>
<td>1,764</td>
</tr>
<tr>
<td>Ammonium nitrate</td>
<td>33.5 - 34.5</td>
<td>2,302</td>
</tr>
<tr>
<td>Calcium ammonium nitrate</td>
<td>25 - 28</td>
<td>2,579</td>
</tr>
<tr>
<td>Nitrogen solutions (mainly UAN)</td>
<td>28 – 32</td>
<td>1,290</td>
</tr>
<tr>
<td>Ammonium sulphate</td>
<td>21</td>
<td>255</td>
</tr>
<tr>
<td>Other straight nitrogen</td>
<td></td>
<td>391</td>
</tr>
<tr>
<td><strong>Multi-nutrient fertilizers</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NPK</td>
<td>5 – 25</td>
<td>1,982</td>
</tr>
<tr>
<td>NP</td>
<td>20 – 26</td>
<td>200</td>
</tr>
<tr>
<td>DAP (di-ammonium phosphate)</td>
<td>16 – 18</td>
<td>290</td>
</tr>
<tr>
<td>MAP (mono-ammonium phosphate)</td>
<td>11</td>
<td>-</td>
</tr>
<tr>
<td>NK</td>
<td>13 – 26</td>
<td>17</td>
</tr>
<tr>
<td><strong>Total nitrogen</strong></td>
<td></td>
<td>11,148</td>
</tr>
</tbody>
</table>
Compound fertilizers:
Fertilizers containing more than one of the primary nutrients - nitrogen (N), phosphorus (P) and potassium (K) - are known as compound fertilizers. Their use accounts for 22% of total nitrogen consumption in western Europe.

There are two distinct types:

- **Blended fertilizers** are produced by the dry mixing of granules or particles of two or more intermediate fertilizer materials. In good-quality blends the component particles are precisely matched in respect of size and some other physical characteristics. If components are not correctly matched they can separate (segregate) during handling, transport and spreading, which can result in uneven distribution of nutrients on the field.

- **Complex fertilizers** containing at least two of the nutrients N, P or K are usually obtained by chemical reaction. They have the advantage of having each of the component nutrients in every granule.

The majority of compound fertilizers applied in western Europe are complex fertilizers. The granules of these fertilizers are of a uniform size range and have a defined composition; they therefore present no risk of segregation.

In addition to the quality checks by manufacturers, fertilizer quality in EU countries is also controlled by official institutions.
Speciality fertilizers.
Under specific meteorological and soil conditions, immobilisation, denitrification, volatilisation or leaching of nitrogen may occur, thus reducing fertilizer efficiency. In response, the fertilizer industry has developed special types of fertilizers designed to reduce such effects. These special types can be listed as follows:

Foliar fertilizers.
In certain situations nitrogen can be very efficiently taken up through the leaves of plants, and this application method can be used to avoid immobilisation or leaching of soil-applied nitrogen. However, the quantity of nitrogen which can be applied using foliar sprays is limited and in practice these are used to supplement soil-applied nitrogen.

Slow-release and controlled-release fertilizers.
A slow or controlled release fertilizer contains nitrogen and maybe other nutrients in forms that delay its initial availability or extend its availability over time, ideally to match the uptake by the crop. Typically, a slow release fertilizer relies on the inherent water insolubility of the nitrogen-containing material, while a controlled release fertilizer is made through modification of the soluble fertilizer product, such as coating or encapsulation. The two major groups of slow and controlled-release fertilizers, according to their production process, are:

- **Slow-release fertilizers**:
  Urea-aldehydes (urea-formaldehyde UF, isobutyliden-diurea IBDU, crotonoliden-diurea CDU) designed mainly for professional use on turf, in nurseries and in gardens.

- **Controlled-release fertilizers**:
  These materials are designed to release nutrients over a given period (3, 6, 9 or 12 month) through a coated surface or through an encapsulating membrane.

Foliar fertilizer cannot provide all the nitrogen a crop needs, but it can support the soil supply in periods of active growth. Here a calcium nitrate solution is applied to prevent bitter pit.

The availability of nutrients can be delayed by coating the fertilizer with a thin polymer layer.
Stabilised fertilizers: fertilizers associated with nitrification inhibitors.

Nitrification inhibitors are chemical compounds that delay bacterial oxidation (nitrification) of ammonium nitrogen by suppressing the activity of Nitrosomonas bacteria in the soil. The objective is to preserve applied ammonium nitrogen in its original form, which is stable in the soil, and to slow its conversion to nitrate. This temporarily lessens the proportion of nitrate in the soil thereby reducing potential leaching losses or formation of $\text{N}_2\text{O}$, both of which can result from high rainfall or irrigation.

The costs of controlled-release or stabilised fertilizers are significantly higher than those of conventional fertilizers. Thus, their main uses are restricted to high value crops, specific cultivation systems and non-agricultural higher-value sectors (horticulture, nurseries, greenhouses, etc). World consumption of manufactured slow and controlled-release fertilizers in 1995 was estimated at about 560 kt of product.

A specialised hall in which fertilizer spreaders and fertilizer spread patterns are tested.
Regulations.

Fertilizer standards.
The regulation of fertilizer marketing to protect the consumer against fraud was introduced early in European countries, for example in 1888 in France. At the first international congress of applied chemistry in Brussels in 1899 efforts were made to define the methods of analysis for fertilizers traded internationally. In 1903 ‘regulations of analytical methods for mineral fertilizers and feeds valid in international trade’ were accepted.

From 1976 to 2003, fertilizer marketing in the EU was regulated by the directive 76/116/EEC. This regulation was designed to ensure uniformity of definitions, labelling and analytical requirements throughout the EU, to facilitate trade by standardising fertilizer types and to guarantee product composition and effectiveness to farmers. Fertilizers meeting the requirements of the regulation could be labelled an ‘EC Fertilizer’ and could be freely traded within the EU.

Not all fertilizers on the market in individual Member States were covered by the original directive, and these had to be subject to national regulation. More fertilizers have been added to the EU list of types, but some are still regulated as national fertilizers.

The 76/116/EEC Directive was recently replaced by a new regulation (EC) 2003/2003 of 13 October 2003. This regulation includes additional requirements for safety measures concerning ammonium nitrate fertilizers with high nitrogen content. Furthermore, manufacturers and importers are required to facilitate the traceability of such fertilizers.

Physical quality of European fertilizer.
Uneven distribution of fertilizer in the field leads to localised over- and under-supply. It can reduce the agronomic efficiency of fertilizers through lower yields and reduced crop quality and may have undesirable environmental impacts. European fertilizer manufacturers set themselves high standards of physical product quality.

For straight or compound fertilizers the evenness of spreading is highly dependent on physical quality. Density, particle size and size distribution, hardness and surface texture are characteristics of fertilizers which have major effects on application accuracy:

- Low density particles can cause spreading problems through spinning disc spreaders because they may not be thrown sufficiently far.
- Wide variation in particle size will affect both the uniformity of flow rate and the transverse spread pattern.
- Particles which are sufficiently hard will resist fragmentation in the spreading mechanism, and a free-flowing fertilizer is essential for a uniform application rate.

The nutrient content, the form of nitrogen and the solubility of the phosphate have to be declared on the fertilizer bag or in the delivery documents to avoid confusion or fraud.
Nitrogen, environment and health

The use of nitrogen fertilizers has been essential to the doubling of global food production in the past 50 years. This implies that today substantially more nitrogen circulates through the various compartments of the global nitrogen-cycle. In some cases this is also connected to increased nitrogen transfers to water and air with associated potential environmental effects.

**Nitrate leaching.**

The mineral nitrogen in the soil is mainly nitrate (NO\(^3^-\)) and to a lesser extent ammonium (NH\(_4^+\)). As nitrate is minimally adsorbed onto soil particles, it is very mobile and therefore susceptible to leaching. During the vegetative period of a crop the risk of nitrate leaching into groundwater is low because once established the plants take up most of the nitrate available in the soil. Furthermore virtually no downward water movement occurs during this vegetative period due mainly to the high evapotranspiration of plant and soil. During a vegetation-free period from late autumn to early spring, precipitation often exceeds evapotranspiration from plants and soil.

With the exception of occasional extremely wet summers, any leaching of nitrate in Europe generally starts only after the soil is fully saturated with water in early winter (Figure 13).

Any fertilizer nitrogen that has not been taken up by the crop or nitrogen that is mineralised from soil organic matter, crop residues or manure applied outside the growing period can be leached downwards through the soil profile. The quantity of crop residue and the nitrogen use efficiency is crop-specific. The length of the periods without crop coverage depends on the rotation practised by the farmer.

![Figure 13](image-url): Relationship between rainfall, quantity of drainage water (leachate) and amount of nitrogen leached from the soil (Limburgerhof, Germany).
Figure 14 shows nitrate leaching and nitrogen removal (i.e. the nitrogen in the harvested product) with and without the use of nitrogen fertilizer for different cropping systems and for bare soil.

The Figure reveals that the cropping system influences nitrate leaching more than the nitrogen fertilization itself. Under fallow land, where there are no plants to take up water and nutrients, leaching is highest even on unfertilized plots. In an arable or horticultural rotation fertilization increases leaching losses. But when 160 kg N/ha is applied, most of this additional nitrogen is taken up and removed with the crop. Leaching is only slightly increased in the arable rotation, although somewhat more in the horticultural rotation, due to its specific conditions of short duration crops with limited root systems (see page 53). Under permanent grass very little nitrate leaching occurs even when fertilizer is applied.

The arable farmer therefore has to avoid untimely mineralisation of soil organic matter by ploughing as late in the year as possible or by no- or minimum-tillage. Furthermore he should try to keep some crop cover in the field as long as possible by choosing his crop rotation carefully and by including ‘catch’ crops (such as mustard) which are subsequently ploughed into the soil.

Green manure crops such as mustard shown here can substantially reduce nitrogen leaching over winter.
Influence of mineral fertilizer.
In addition to other factors (see Box 4), fertilizer rate and timing can influence the leaching of nitrate. During late autumn and winter leaching is independent of the amount and type of fertilizer which was applied during the growing season, provided that this nitrogen was used by the crops during spring and summer. Figure 15 shows that the leaching risk only increases significantly when the rate of nitrogen applied exceeds the nitrogen requirement of the crop. Up to the optimum yield the leaching risk remains constantly low, because the crop uses almost all the applied nitrogen, but it increases significantly when additional nitrogen is no longer transformed into yield.

Figure 15: Relationship between nitrogen input, crop yield and nitrogen leaching potential. (Baumgärtel et al, 1989).

Gaseous losses

Emissions of nitrogen compounds to the atmosphere are part of the natural nitrogen cycle (see Figure 2, page 7). From an environmental perspective ammonia and nitrous oxide are the most relevant gases within the N-cycle. When deposited onto the soil, usually in rainfall, ammonia contributes to acidification and the potential eutrophication of natural eco-systems, whereas N₂O is a strong ‘greenhouse gas’.

Ammonia volatilisation.
In the EU-15 the European Environment Agency estimated in 1998 that more than 90% of the total emissions of the volatile gas ammonia are related to agriculture, with animal husbandry making by far the greatest contribution to the total ammonia released to the environment (74% in 1990, ECETO C¹, 1994). Ammonia volatilisation begins immediately after the excretion of urine or faeces by the animal and continues during storage and application of these organic fertilizers.

¹ European Centre for Ecotoxicology and Toxicology of Chemicals.

Box 4
Factors influencing nitrate leaching:
- Soil texture (water-holding capacity, clay content).
- Water balance (precipitation/irrigation – evapotranspiration).
- Rooting depth of the crop.
- Nitrogen balance (N input – N output).
- Timing and amount of nitrogen mineralised from organic fertilizer sources (manure, sewage sludge, crop residues).
- Plant coverage: crop rotation, underseeding, intercropping, catch-crops (e.g. mustard, phacelia).
- Crop type (growing period, harvest date, type/quantity of residues).
UNDERSTANDING NITROGEN AND ITS USE IN AGRICULTURE

Mineral fertilizers contribute about 10% to the total ammonia emissions, but there are differences between fertilizer types. Urea and some ammonium based mineral fertilizers have a relatively high potential for ammonia emissions under certain conditions. Ammonia losses are highly variable and dependent on soil, climate and management factors (see Box 5). For mineral fertilizers average ammonia losses vary between zero (for pure nitrate fertilizers), 1-3% (ammonium nitrate), 8% (urea/ammonium nitrate solution) and 15% and more for surface-applied urea (ECETOC, 1994).

Nitrous oxide emissions.
All ecosystems emit nitrous oxide (N\textsubscript{2}O). In fact more than 50% of the global emission of N\textsubscript{2}O is considered ‘natural’ (soils under natural vegetation, oceans, etc.). About 30% is estimated to arise from agriculture, although this includes the N\textsubscript{2}O emission agricultural soils, which cover 11% of the dry surface of our planet, would have generated naturally if they had been left undisturbed. N\textsubscript{2}O itself contributes 6% to the total global warming potential, according to the Intergovernmental Panel on Climate Change (IPCC, 2001).

Of the anthropogenic N\textsubscript{2}O emission, animal husbandry is again responsible for the largest share (54%), while mineral fertilizers are estimated to lead to about 17%. Two microbial processes in the soil are responsible for the N\textsubscript{2}O emissions in agriculture: denitrification and, to a lesser extent, nitrification (see page 13). Different interactions between soil, climatic and agricultural management factors influence the share of nitrification and denitrification and the total amount of N\textsubscript{2}O emitted (see Table I, next page).

Anaerobic conditions are a prerequisite for N\textsubscript{2}O emissions via denitrification. Furthermore the quantity of nitrogen available in the soil is an important factor affecting the amount of N\textsubscript{2}O released. As denitrifying micro-organisms need organic carbon as an energy source, the availability of degradable organic matter is a further limiting factor for N\textsubscript{2}O formation. In practice it is very difficult for the farmer to avoid or even reduce substantially this sort of emission. He has to have the ploughed layer well aerated to support root growth and he has to maintain the soil organic matter content at an appropriate level to stabilise the soil structure.

**Box 5**

**NH\textsubscript{3} volatilisation is increased by:**
- high soil pH,
- low H\textsuperscript{+} buffer capacity,
- high temperature / radiation,
- high wind speed.

**NH\textsubscript{3} volatilisation is diminished by:**
- high infiltration capacity,
- high clay content,
- increasing organic carbon (> 1.5% org. C),
- sufficient soil moisture,
- precipitation / irrigation after application,
- incorporation into soil.
Based on Bouwman (1995), the IPCC estimates the mineral fertilizer-induced N\textsubscript{2}O emissions to be 1.25% of the applied fertilizer nitrogen. However, Bouwman et al (2002) recently revised their N\textsubscript{2}O estimation procedure and now propose new generally reduced N\textsubscript{2}O emission factors but with higher values for urea than for nitrate-containing nitrogen fertilizers.

Ammonia emission from grazed pasture has been studied intensively.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Effect on N\textsubscript{2}O emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil aeration</td>
<td>• intermediate aeration → highest N\textsubscript{2}O production.</td>
</tr>
<tr>
<td></td>
<td>• low aeration → high denitrification rate, but mainly N\textsubscript{2}.</td>
</tr>
<tr>
<td>Soil water content</td>
<td>• increasing soil water content → increasing denitrification, but under very wet conditions mainly N\textsubscript{2}.</td>
</tr>
<tr>
<td></td>
<td>• changing conditions (dry/wet) → highest N\textsubscript{2}O production.</td>
</tr>
<tr>
<td>N availability</td>
<td>• increasing NO\textsubscript{3}/NH\textsubscript{4} concentrations → increasing N\textsubscript{2}O emissions.</td>
</tr>
<tr>
<td>Soil texture</td>
<td>• from sand to clay → increasing N\textsubscript{2}O emissions.</td>
</tr>
<tr>
<td>Tillage</td>
<td>• ploughing → lower N\textsubscript{2}O emissions.</td>
</tr>
<tr>
<td></td>
<td>• no/low-tillage → higher N\textsubscript{2}O emissions.</td>
</tr>
<tr>
<td>Compaction</td>
<td>• increasing compaction → increasing N\textsubscript{2}O emissions.</td>
</tr>
<tr>
<td>Soil pH</td>
<td>• where denitrification is main source of N\textsubscript{2}O emission: increasing pH results in decreasing N\textsubscript{2}O emissions.</td>
</tr>
<tr>
<td></td>
<td>• where nitrification is main source of N\textsubscript{2}O emission: increasing pH results in increasing N\textsubscript{2}O emissions.</td>
</tr>
<tr>
<td>Organic material</td>
<td>• increasing organic carbon content → increasing N\textsubscript{2}O emission.</td>
</tr>
<tr>
<td>Crops and vegetation</td>
<td>• plants, but especially their residues and remaining roots after harvest, increase N\textsubscript{2}O emission.</td>
</tr>
<tr>
<td>Temperature</td>
<td>• increasing temperature → increasing N\textsubscript{2}O emission.</td>
</tr>
<tr>
<td>Season</td>
<td>• wet summer → highest N\textsubscript{2}O production.</td>
</tr>
<tr>
<td></td>
<td>• spring thaw → high N\textsubscript{2}O production.</td>
</tr>
<tr>
<td></td>
<td>• winter → lowest N\textsubscript{2}O emission.</td>
</tr>
</tbody>
</table>

Table I: Factors influencing N\textsubscript{2}O emission rates.

Gaseous losses from grazed grassland – a particular problem.

While small losses of nitrogen occur from mown grassland, the situation under grazing is different. In grazed pastures the greatest point sources of nitrogen are urine and dung patches with localised nitrogen rates equivalent to more than 1,000 kg N/ha, for cattle. These rates are well in excess of plant demands and can lead to significant nitrogen losses. On average 3.5% of the urine-N is lost as N\textsubscript{2}O, another 20% as NH\textsubscript{3} (Ledgard, 2001).

As these losses are unavoidable farms with a high proportion of grazing are bound to have a higher nitrogen balance surplus (see next page).
Minimising nutrient losses and pollution.

Nitrogen balance as a suitable management instrument.

The nitrogen balance compares the nitrogen input (e.g. from fertilizer, biological nitrogen fixation, feedstuffs) with the nitrogen output (e.g. in the harvested crop, milk, meat) on a field or farm basis. As weather conditions and crops vary between years, N-balances should only be interpreted as annual averages of a crop rotation or over 4 to 5 years on grassland. A certain nitrogen surplus has to be accepted to keep the soil-N in a steady state because agriculture takes place in an open system where even under the conditions of best practice some losses, as described on previous page, are inevitable. The level that has to be accepted depends on natural conditions (sandy soil > clay soil, high rainfall > low rainfall) and on the production system of the farm. For arable farms it is lower than for vegetable growers and livestock farms. A nitrogen surplus above an acceptable level may indicate that there are some losses of nitrogen from the field/farm to the environment which could be reduced.

Because sufficient measurements of nitrogen emissions to water and air are difficult to obtain on a large scale, the N-balance is an useful indicator of the contribution by agriculture to any nutrient enrichment of the environment at farm, regional or national level.

N-balance is a suitable management instrument:

- to estimate the scale of nitrogen losses from agriculture on national, regional or farm bases;
- to monitor developments over time.

N-balance gives no information on:

- the optimum nitrogen fertilizer rate;
- the contribution of different types of nitrogen losses (nitrate, ammonia, nitrous oxide).

Box 6

Good management practice to minimise nitrogen losses:

- Fertilizer timing and rate adjusted to crop demand to avoid incorrect and untimely nitrogen inputs:
  - Application timed and split to crop needs and development stage.
  - No application outside the growing period or prior to fallow period.
  - Application at optimum rates according to a fertilizer plan.
  - Adjust fertilizer plan during the vegetative period, e.g. based on plant analysis.
  - Balanced plant nutrition of all nutrients that support nitrogen use efficiency.
- All-year-round plant coverage (intercropping, catch crops) to avoid periods with bare soil.
- Efficient use of animal manure and sewage sludge:
  - Application in spring when plants can best utilise manure nitrogen.
  - Sophisticated application techniques and rapid incorporation to minimise losses.
- Incorporation of straw to immobilise mineral nitrogen before winter.
- Soil tillage in spring to reduce nitrogen mineralisation following autumn and winter cultivations.
Figure 16 shows the regional N-balances for the EU-15 countries in 1997 (Eurostat, 1997). A particularly high surplus of more than 170 kg N/ha is calculated for the Benelux countries, which can be mainly attributed to high stocking rates in animal husbandry. The strong relationship between the N-balance and the agricultural production system can also be clearly seen from Figure 17. The nutrient surplus in animal production is significantly higher than in crop production mainly because the nutrients contained in manure can rarely be used as efficiently for crop production as nutrients from mineral fertilizers (see pages 41 to 44).

Figure 16: The nitrogen balance surplus correlates strongly with the stocking density.

Figure 17: Relationship between the nitrogen balance surplus (kg N/ha), and stocking density (animal units/ha), data from 335 sites in Germany, 1999.
Life Cycle Assessment to evaluate the environmental impact of fertilizer use.

The N-balance gives valuable general information, but it cannot distinguish between the different pathways of loss, neither can it evaluate the potential environmental impact of the nitrogen losses. Furthermore, agriculture in general and fertilizer use in particular contribute to a wide range of environmental impacts, which are not only related to on-farm effects. The Life Cycle Assessment (LCA) methodology is especially designed to analyse systematically and to evaluate all environmental impacts that arise in a production system. Figure 18 shows results from an LCA study investigating the environmental impact of different fertilizer rates in European wheat production. The study revealed that the sub-optimal treatment (96 kg N/ha) had the smallest environmental impact, but that the environmental index of the economic optimum rate (192 kg N/ha) was only slightly greater.

Compared to the economic optimum rate, the reduced nitrogen rate contributed less to global warming and eutrophication, but due to lower yields per hectare its contribution to acidification and land use was higher. Without nitrogen fertilizer the total environmental burden was clearly higher, mainly because of the increased land requirement per tonne of wheat grain produced.

Figure 18: The combined environmental burden for two nitrogen rates on a crop of wheat compared with the unfertilized crop expressed as the environmental index per tonne of grain. The lower the index the better for the environment. (Brentrup, 2003).
Nitrate and human health.

The general public perception is that dietary nitrate intake poses a health risk and therefore levels of nitrate in agricultural products and drinking water should be minimised. The World Health Organization (WHO, 1970, modified in 1993) set a recommended limit for drinking water of 50 mg NO$_3^-$ per litre with a maximum level of 100 mg NO$_3^-$ per litre. The lower WHO figure was taken as the upper limit in the EU Drinking Water Directive (1980), the EU Nitrate Directive (1991) and in the Water Framework Directive (2000).

Ingested nitrate is rapidly excreted with the urine and usually does not accumulate or interfere negatively with the human metabolism. The main issue was the microbial reduction of nitrate (NO$_3^-$) to the more active nitrite (NO$_2^-$), which was stigmatised by its chemical relationship to nitrosamines and methaemoglobin.

There is now widespread agreement that the human health concerns over nitrate, which led to the introduction of the WHO recommendations in 1970, were largely unfounded. The cause of methaemoglobinaemia in babies for example, which gave rise to the so-called ‘Blue Baby Syndrome’, was shown some years ago to have been associated with shallow and polluted wells and not caused directly by ingested nitrate as originally supposed.

Infantile methaemoglobinaemia was first described in the 1940s. It was found that nitrite reacted with the haemoglobin of the blood and blocked its oxygen-carrying capacity. (The lack of oxygen caused the ‘blue’ colour of the baby.) In adults a specific enzyme keeps the concentration of methaemoglobin below 1-2%, but this enzyme system is not fully developed in infants younger than 6-12 months. An elevated level of ingested nitrate (from water with a high nitrate content) was originally believed to have been the cause of ‘Blue Baby Syndrome’. Over the past 20 years a more complex picture has emerged.

Nitric oxide (NO) is produced endogenously in response to enteric infection and inflammation as part of the mammalian immune response. Nitrite (NO$_2^-$) is a product of nitric oxide metabolism. It was therefore proposed that nitrite produced in response to gastrointestinal infections / inflammations (and not from ingested nitrate) is primarily responsible for infantile methaemoglobinaemia (Avery, 1999).
This hypothesis is supported by several findings, e.g.:

- Infants suffering from diarrhoea and methaemoglobinemia (without exposure to nitrate contaminated water) excreted up to ten times more nitrate than they ingested.
- Gastroenteritis infections in adults are associated with substantial endogenous NO production and elevated plasma nitrate levels.
- An epidemiological study showed that the number of cases of methaemoglobinemia from urban areas (with low concentrations of nitrate in drinking water) varied seasonally with peaks corresponding to the time period when infectious gastroenteritis is most common.

Similarly, the theoretical association of the incidence of gastric cancer with the ingestion of nitrate, which was never supported by practical evidence, has been shown to be only a supposition. Indeed recent work suggests that ingested nitrate provides gastro-intestinal protection against food borne pathogens. These recent findings are endorsed by the fact that 'vegetables have consistently been shown to reduce cancer risk' (US National Research Council, 1995), despite vegetables being the largest source of ingested nitrate.

Furthermore, the European Commission Scientific Committee for Food concluded, in its 'Opinion on Nitrate and Nitrite' of 22 Sept 1995, that "long-term animal studies did not indicate that nitrite or nitrate per se are carcinogenic and that there was no quantitative evidence for the endogenous formation of carcinogenic N-nitroso compounds after exposure to realistic levels of nitrate and N-nitrosatable precursors". In addition, the Committee concluded that "overall, extensive epidemiological studies on nitrate have failed to demonstrate an association with cancer risk in man" (EC, 1995).

Box 7

"Blue Baby Syndrome"

Methaemoglobinemia can kill infants less than one year old. However, the American H. H. Comly who first reported the problem in 1945 called it 'well-water methaemoglobinemia', and all the cases identified in a 1991 book on the nitrate issue were caused by water from wells, 98% of which were described as 'privately dug'. Amateur well-diggers may well have dug too close to other household 'facilities', and this may be why in a number of reports the water was polluted with bacteria as well as nitrate.

In conclusion, these findings make it difficult to justify further restrictions for nitrate levels in drinking water or in agricultural products such as vegetables. On the other hand reasonable measures designed to limit nitrate input from agriculture into ground- and surface- waters are still valuable from an environmental and economic perspective, as already discussed on page 44. However, the costs to the European taxpayer and consumer which arise from the current health-related legislation limiting the nitrate content in drinking water supplies may justifiably be reconsidered, in the light of the better scientific understandings gained since the 1970s.

Over the last 20 years, dietary nitrate has been implicated in the formation of methaemoglobin and carcinogenic nitrosamines in humans. This has led to restrictions of nitrate and nitrite levels in food and drinking water. However, there is no epidemiological evidence for an increased risk of gastric and intestinal cancer in population groups with high dietary vegetable or nitrate intake. A re-evaluation of our currently very negative perception of dietary nitrates comes from recent research into the metabolism and enteral-salivary circulation of nitrate in mammals. These studies showed that nitrate is converted to nitrite in the oral cavity that then 'fuels' an important mammalian resistance mechanism against infectious diseases. Moreover, there is now evidence that the conversion of nitrate into oxides of nitrogen prevents the formation carcinogenic nitrosamines.

Nitrogen fertilization

Fertilizing strategies for crops.

Fertilizer applications are calculated to provide the lowest rate necessary to obtain the optimum crop yield achievable at the specific site, and to ensure that the quality of the crop is appropriate to its intended use.

Depending on the nutrient being applied, this objective can be reached by various fertilizer practices. For nutrients such as P, K and magnesium (Mg), which are relatively immobile in the soil and thus do not move significantly out of the rooted soil layer unless taken up by plants, the amount of the nutrient removed in the harvested crop should be returned to the soil. If soil analysis shows an insufficient reserve buffer of the respective nutrient, increased application rates are necessary so that after a few years a satisfactory soil nutrient level is obtained.

For a mobile nutrient such as nitrogen it is not possible to use such a system because mineral nitrogen is not retained in soil in the same way and could not be relied upon to be available when required by the crop. The grower will usually meet the needs of the crop by using several separate applications of nitrogen during the vegetative period to prevent nitrogen deficiency even in periods of peak demand as well as to ensure no oversupply.

Moreover, nitrogen application offers the possibility to:

• manage the development of the crop, i.e. to influence the yield by the promotion or indirect inhibition of individual yield components; and
• directly improve the yield quality by the timely application of prescribed amounts of nitrogen at defined stages of plant development.

Such fertilizer strategies are widely used, for example, in the yield and quality management of cereals, which occupy more than 50% of the EU arable land. Some of the strategies employed by European farmers in their use of nitrogen fertilizers are detailed below for a number of farm crops.

Nitrogen fertilization of cereals.

As soon as a cereal crop begins active growth in the spring and starts to ‘thicken up’, producing many new shoots (the tillering stage), the plants begin to take up large quantities of nitrogen, which continues until the grain is at the milky-ripe stage (the grain contents are like milk). With an adequate water supply, the crop needs 4–5 kg N/ha per day during this period. Cereals take up about 40% of their total nitrogen requirement up to the end of tillering, an additional 20% up to emergence of the ear, and the remaining 40% up to the start of physiological maturity. The amount of nitrogen stored in the grains and thus removed with the harvest can vary considerably (Table J) depending on the yield and the protein content.
UNDERSTANDING NITROGEN AND ITS USE IN AGRICULTURE

Table J: Nitrogen removal by cereal grain with differing crude protein contents and yields, in kg N/ha.

The grain yield of a cereal plant is determined by three factors:

- the number of ear-bearing stalks,
- the number of grains per ear, and
- the average weight of the grains.

During the development of the cereals, these three yield components effect each other, both positively and negatively. For example, a large number of ear-bearing shoots will result in a relatively low number of grains per ear and a lower grain weight. By adjustment of the nitrogen applications and their timing the development of these yield components can be managed to a certain extent.

**Number of ear-bearing shoots.**
Cereals are able to auto-regulate the number of ear-bearing shoots per plant during the tillering stage. The extent to which tillering takes place depends, among other things, on the nutrient supply, especially on the amount of nitrogen available to the individual plant. This gives the grower an excellent means of optimising the number of ears per unit area. When the nitrogen supply per plant is insufficient, e.g. due to a low fertilizer rate or a high seed rate, the individual plants produce only few ear-bearing shoots. Vice-versa, tillering is promoted by an ample nitrogen supply. Too high a rate, however, leads to excessively dense crop stands with high competition between the shoots which then produce fewer and smaller grains per ear. As a result, the yield per area is reduced and the risk of lodging after a thunderstorm or fungal infection is increased.

Figure 19: Timing of nitrogen applications in relation to the development of nitrogen uptake and yield components of winter wheat. A large number of ear-bearing shoots and grains per ear are initiated and are later reduced in accordance with the growing conditions to sustainable numbers.
Therefore, the rate of the first nitrogen application in the early spring depends strongly on the plant density in the cereal field. After a severe winter, during which many plants may have died, winter cereal stands are frequently weak and thin in spring. By applying a substantial amount of nitrogen at the start of vegetative growth, the grower can promote tillering so that losses in plant numbers are compensated by an increased number of ear-bearing shoots per plant.

After a mild winter, however, the crops are generally dense and well developed, as almost all seedlings will have survived the cold season. In this case, the grower will support the further growth by applying a carefully calibrated nitrogen dose, but will avoid stimulating tillering that would lead to an excessively dense crop.

**Number of grains per ear.**
The number of grains per ear is determined immediately after tillering (see Figure 19). Initially, a maximum number of grain primordia are formed, followed by a reduction which is controlled by the supply of nutrients, water and light. High competition between the individual plants for these inputs results in a severe reduction of the number of primordia, whereas with low competition only few of the initiated grains die off.

With the help of the second nitrogen split application, generally given at the time of tillering, the grower plans to affect the primordia reduction in a way that gives the optimum ratio of ear-bearing shoots to grains per ear. Having more grains per ear than can be filled during ripening leads to small grains of low quality.

**Grain weight.**
The third yield component, the weight of the individual grains, is mainly genetically determined, but is also influenced by climatic conditions and nutrient supply. Moreover, there is a negative relationship: the higher the number of grains per ear the lower will be the weight of the individual grains.

The 'filling' of the grains depends essentially on the assimilative performance of the cereal crop during the period from heading to maturity. A late nitrogen top-dressing at the ear-emergence stage can improve the grain-fill by increasing the leaf area and raising the chlorophyll content.

**Fertilization for quality.**
A late top-dressing of nitrogen can not only assist with grain fill, but can also directly raise the protein content of the grains. High protein content of the grain is a desirable trait for feed grain to contribute as much as possible towards meeting the animal's protein needs. When the grain is to be used for bread-making, a high protein content of the wheat is essential for good baking quality (see page 60). A late nitrogen top-dressing ensures that the grains reach their genetic potential for baking properties.

However, such a late nitrogen top-dressing is not carried out on barley grown for malting, because breweries and distilleries require grain with a low protein content (<11.5% crude protein) and high in starch.
Nitrogen fertilization of potatoes.
The tuber yield of a potato plant is the product of the number of shoots per plant, the number of tubers per shoot and the tuber weight. Whereas the influence of a nitrogen application on the first two parameters is only limited, it has a major effect on tuber weight by determining duration and intensity of the starch accumulation in the tubers.

A high nitrogen supply inhibits tuber initiation in spring, whereas insufficient overall nitrogen nutrition leads to the premature death of the assimilating above-ground parts of the potato plant. For these reasons, and because potatoes have a relatively shallow and limited root system, the nitrogen fertilizer is usually applied in two separate dressings, the first at planting and the second usually immediately after tuber initiation.

The nitrogen rate for potatoes depends considerably on the end-use of the crop.
When potatoes are grown for industrial processing, i.e. for the production of starch or alcohol, it is advantageous to keep the crop growing in the field as long as possible, in order to prolong the tuber-filling process; a limited nitrogen supply would lead to a reduced yield.

Potatoes for direct consumption which receive too much nitrogen have a reduced storage life and are prone to quality-reducing tuber defects (cavities, cracks). Early potatoes, however, require higher nitrogen rates to speed up growth so that they can be harvested early. They are not meant to be stored for a long time.

In contrast, the nitrogen rate for seed potatoes should be moderate to avoid unwanted large tubers and delayed tuber ripening (caused by a continued nitrogen supply at maturity). Seed potatoes are harvested early to reduce the risk of infection by fungal or virus diseases.

Following a crop of early potatoes, an unfertilized catch crop should be grown to take up the mineralised and residual nitrogen left in the soil. When not used as fodder, the plant material thus produced can be ploughed under as green manure before the next crop is sown. The harvest of potatoes necessarily leads to an intensive aeration of the soil. This increases the mineralisation of organic matter and the liberation of nitrogen and catch crops should always be considered in these circumstances.

Vegetable cultivation.
All broad-field agricultural crops, such as cereals, oilseed rape and potatoes, stop their active growth once they have reached maturity. By that time, if during the vegetative period the crop growth was not affected by drought, fungal or pest attack, hardly any plant-available nitrogen should be found in the rooted soil. Provided that the applied fertilizer rate has been correct, the plants will have depleted the soil completely. This is totally different for short-cycle vegetables.
Cereals, rape, beet and maize crops produce roots down to a depth of 1.5 m or more, and the root system under one square metre of winter wheat can reach a total length of over 30 km. However the roots of many fast growing vegetables penetrate only down to 0.1 - 0.3 m and the total root length, for example of a spinach crop, is only about 2 km/m². Such a small root system exploits less soil volume than that available to agricultural crops. However, the rate of assimilation that vegetables have to achieve is comparable, as they need to reach marketability in 4 weeks (lettuce) to 8 weeks (kohlrabi). Therefore, they require a permanently high nutrient concentration in their restricted rooted soil volume, because spinach for example may take up more than 10 kg N/ha per day. The fertilizer application is therefore generally split into a basal application before sowing or planting followed by one or two top-dressings.

Many kinds of vegetables, such as lettuce and spinach, are harvested while still in full growth, before they have reached physiological maturity. At harvest the soil therefore has still to be well supplied with nitrogen to safeguard the production of marketable qualities.

The nitrogen which remains in the soil after the harvest must be prevented from leaching by immediately establishing the next crop or a catch crop. To monitor the residual soil nitrogen, vegetable growers have their soils regularly tested for available nitrogen, often several times per year.

**Soft fruit.**
Young strawberries, for example, are planted in late summer and usually get about 40 to 60 kg N/ha to support the establishment of the plants before winter. In spring professional growers have their fields tested for plant-available nitrogen. It is very critical to apply sufficient but not too much nitrogen in spring. An oversupply not only stimulates the leaf-growth and reduces the number of flowers but also leads to soft fruits susceptible to fungal attack.

**Permanent crops.**
Once established, permanent crops like fruit trees or grape vines maintain a substantial proportion of their nutrients in a closed cycle. Nutrients from decomposing leaves and prunings are recovered by the deep root system. The amount of nitrogen to be applied annually depends on the variety and the yield level and may vary considerably.

**Top fruit.**
As a general guide, apple orchards for example receive 60 to 80 kg N/ha annually. About half of it is applied after harvest. This avoids any negative influence on the ripening fruit and extra vegetative growth, but it stimulates the photosynthesis so that sufficient reserves are stored in the tree as it recovers from fruiting. This supports the initiation of more and stronger flower buds for the next spring. In spring the grower has to be careful because too much nitrogen initiates strong vegetative growth instead of fruit growth and increases alternate bearing.
Vines.
The cultivation of grape vines varies quite significantly throughout Europe as does fertilization practice. Generally, between 20 and 60 kg N/ha are applied, in northern countries more than in the south, and for white varieties more than for red. The date of application depends on the seasonal rainfall. In a Mediterranean climate it has to be early in the season so that the last rains will carry the nutrients into the soil; in northern countries it should be later, generally at flowering, to avoid nitrate leaching. An adequate nitrogen nutrition is not only needed for the development of the plant, but the grape juice when pressed must contain sufficient nitrogen available to the yeast for fermentation. Too much nitrogen leads to unwanted vegetative growth which means unproductive water consumption and increased susceptibility to fungal diseases.

Grassland.
In contrast to the arable crops which have to be newly established each year, the sward of grassland regenerates itself constantly from its multiplying plant community. Old grass swards have at the soil surface a ‘thatch’ layer formed of dead plant material and are characterised by an increased content of organic matter in the top-soil. Therefore, the amount of nitrogen accumulated in the upper soil layer is generally higher than in arable soils. By the microbial degradation and transformation of dead organic matter, nutrients are constantly released and again become available. On the other hand, this soil-released nitrogen, as well as fertilizer nitrogen, is immediately absorbed by roots or by micro-organisms.

Although the growth rate of the vegetation mass varies significantly in the course of the year, the sward remains physiologically active on all frost-free days. The uppermost 15-20 cm of the soil are so densely rooted that these roots take up all available nitrogen, even in times of reduced assimilation during the cold and dark winter.

Nitrogen application to grassland has the objective of supporting the natural growth pattern and to stabilise or to increase the share of productive grasses with a high feed value. The first fertilizer dressing is applied in spring at the onset of active growth; the sum of all daily temperatures since the 1st January has been established as a useful indicator for the timing of the first nitrogen dressing. When the accumulated daily temperatures have reached the sum of 200°C, the time is right for the first application in the maritime grassland belt from France to Denmark. As the first grass growth flush yields the largest quantity, the first fertilizer dressing needs to be the largest one. After each cutting, smaller amounts are additionally applied until the end of August when further dressings are no longer justified.

On grazed pastures, significant quantities of nutrients from faeces and urine remain in the field. Although such localised deposition leads to increased losses of nitrogen, the majority will be reused by the plants. Therefore it may be sufficient to apply supplementary fertilizer only after every second or third grazing.

The intensity at which grassland is managed, and thus the nitrogen fertilizer rate required, varies considerably and ranges from unfertilized prairies to intensively used cut and grazed meadows, which receive more than 200 kg N/ha annually, depending on the fertility of the site and the farm’s fodder requirement.
UNDERSTANDING NITROGEN AND ITS USE IN AGRICULTURE

Tools to optimise timing and quantity.

Establishing the correct fertilizer rate for a crop is a complex process which involves many different factors such as type of crop, expected yield, nutrients available in the soil and changes in available nutrients during the growing period. The calculation is based on scientific research and local experience of the farmer. The amount of nitrogen needed by a crop depends on the species, the variety, the intended quality and is almost linearly related with the yield over a large range (Figure, Box 9). For the determination of the optimum nitrogen fertilizer rate, it is important to consider the nitrogen supply from the soil. It includes the inorganic nitrogen content available in the soil in early spring (mineral nitrogen) and the predicted net mineralisation during the growth period.

In several countries soil analysis is used to measure the mineral nitrogen content in the rooting zone at the start of plant growth in spring to improve the decision for the first application. The quantity of nitrogen to be applied in this first dressing is determined by subtracting the amount of mineral nitrogen found in the upper 90 cm of the soil from a standard value calculated from numerous field trials to be the appropriate amount required by the crop at this time.

However, during the subsequent growing season, this available nitrogen may be exposed to conversion processes (Box 1, page 14) which vary both in space and time. The potential of the soil to mineralise nitrogen during the growing season is a soil characteristic which only changes over longer periods, but the actual supply of plant-available nitrogen in a particular year can vary considerably due to weather conditions.

Box 9

When increasing amounts of nitrogen are applied to different plots on the same field, in the same year, on the same crop, the yields obtained from the plots form a typical response curve: depending on the fertility of the site, a certain yield is achieved even when no fertilizer has been applied. This yield increase is almost linear with each additional unit nitrogen applied, until it flattens out when the growing conditions of the site and season, or the genetic potential of the plants, do not allow further yield increase (maximum yield). Eventually, the response may even be negative.

The economic optimum is achieved when the cost of the last unit nitrogen applied is still covered by the value of the additional yield it produces. However, at the time the fertilizer is applied the farmer cannot predict the growing condition nor the final yield at the end of the season. Thus, he bases his calculations on the average of the yield achieved during the last three regular years, excluding exceptionally high or low yields. By this method he balances the risk of not fully exploiting the yield potential of the site against that of wasting fertilizer by oversupply.
On the other hand, the need of the growing crop is also influenced by favourable or unfavourable growing conditions. As a result, the optimum nitrogen fertilizer rate for a specific crop changes from year to year and from field to field. Therefore, methods based only on soil analysis to determine correctly the nitrogen available for the crop have limited reliability. They can serve to estimate the nitrogen dressing needed at the start of growth, but require supporting decisions during the season.

Split nitrogen application strategies based on the actual nitrogen status of the plant can assist growers to adjust the available nitrogen supply several times during the growth period. In this way the problem of a varying nitrogen fertilizer demand in different fields and in different years can be better managed. Thus, during the past 20 years scientists and farmers have focused on methods based on direct plant analysis in the field to determine the optimum nitrogen fertilizer rate for subsequent fertilizer application.

In order to be widely accepted by farmers, any field-specific nitrogen recommendation method should be quick, cost efficient and easy to manage. Several methods have been developed for practical use on farms. Leaving an under-fertilized plot in the field (fertilizer window) is a simple method to assist the decision about the optimal timing of a nitrogen fertilizer application, because it warns when the supply from the soil becomes short. But no information about the optimum amount of fertilizer required can be derived by this method.

Methods which are able to predict the optimum nitrogen rate are normally based on chemical or optical measurements. The nitrate sap test is an accurate plant analysis method to help optimise application timing as well as determine the correct amount of nitrogen required. The recommendation is based on the nitrate concentration in the sap squeezed out of the stem of plants.

**Figure 20**: The amount of nitrogen taken up by a crop depends on the growing conditions of the particular field and varies according to the growing conditions of the year (between the blue lines). The mineralisation of nitrogen from soil organic matter also varies annually (between the red lines). Therefore, the 'correct' application rate of nitrogen fertilizer for the same crop in the same field (yellow arrows) will be different from year to year and may need adjustment during the growing season.

The nitrate concentration in the sap of growing plants is a useful indication of the nitrogen nutrition status.
A further improvement of in-field plant analysis methods is the optical measurement of the crop's nitrogen status by estimation of the chlorophyll content. Small handheld tools, as the ‘GPN’ or the ‘N-Tester’, measure the chlorophyll content non-destructively and directly in the field. Since the chlorophyll content is directly related to nitrogen concentration, the resulting readings offer a quick and easy method to obtain information about the crop’s nitrogen status from which can be estimated the quantity of nitrogen required.

It is well known that soil properties, nutrient availability, crop growth and final yield can vary widely within single fields. As a consequence, the optimum nitrogen fertilizer rate also varies in different parts of a field. Especially on large and heterogeneous fields an application of a uniform fertilizer rate will not meet the optimum in each part of the field and will thus result in areas of over- and under-fertilization with nitrogen.

Since the early 1990s variable rate technology has been developing in order to improve the efficiency of farming inputs and lead to economic and environmental benefits. Variable rate technology, or more generally Precision Agriculture, aims to manage crop variability by tailoring inputs to specific crop needs at any particular part of the field. Variable application of nitrogen is of particular interest because nitrogen has the largest immediate effect on crop growth, yield and quality.

Currently the most effective strategy for spatially variable nitrogen application is based on plant analysis: the measurement of within-field variation in crop growth (biomass) and crop nitrogen uptake (chlorophyll content), respectively. In Precision Agriculture the actual nitrogen status of the crop in different areas of the field is the key factor in determining the pattern of the optimum variable nitrogen fertilizer rate.
The most promising systems for measuring within-field variation in crop growth are based on imaging the crop by remote sensing. Spectral indices derived from the reflectance spectra have been shown to be indirectly related to the nitrogen status of crops. The use of spectral scanning of the crop canopy during the growth period enables farmers to identify areas with different biomass development and nitrogen uptake. Based on such information, spatially variable nitrogen fertilizer application plans can be calculated to meet the optimum in each part of the field, and these can be illustrated using a ‘map’. As for traditional methods of plant analysis the reflectance data have to be agronomically calibrated to derive a fertilizer recommendation from these remotely sensed data.

Remote sensors can be mounted on satellites, aircraft and tractors. Aircraft- and satellite-mounted units are able to cover a large area in a short time; optical systems are dependent on suitable weather conditions although recent work using synthetic aperture radar appears to offer some useful data even through cloud. Tractor mounted sensors provide a more self-contained system which can be used irrespective of cloud cover; they allow real-time measurement and nitrogen application as a single operation. Reliable equipment is now commercially available.

Experimental results and practical experience indicate several potential economic and environmental benefits, including:

- increased nitrogen efficiency
- more uniform crop
- more uniform ripening
- more uniform quality
- easier harvesting
- higher yields

Figure 21: Nitrogen application ‘map’ based on crop scanning by a tractor-mounted N-Sensor™ (winter barley, 25 May 1999).
Plants are the primary source of all nutrients required by humans, whether eaten directly or via meat, milk or eggs from animals. Plant nutrients (fertilizers) have a direct impact on food quality.

Different quality criteria are requested for basic materials for food production:

• palatability
• nutritional value
• healthiness
• processing qualities
• psychological, cultural or ideological criteria

All these categories are influenced positively or negatively by the fertilization – the amount of a single nutrient available or the balance between several nutrients.

Quality food of high nutritional value.

Food quality is one of the major concerns of today’s consumer, and there is no doubt that balanced fertilization is an essential prerequisite for a quality crop and thus quality food. An appropriate supply of available nitrogen, matched with other essential plant nutrients, ensures good protein content and quality, for example by boosting vitamin content.

Cereals.

Across Europe cereal production is perhaps the major activity in arable farming. In addition to providing large quantities of animal feed it supplies a high proportion of all the grain required to produce bread, cakes, pastries, noodles and breakfast cereals as well as beer and spirits.

Cereal products play a central role in the European diet and in the UK, for example, the consumption of bread and other cereal products provide about 25% of the average per capita daily intake of protein.

Carefully planned nitrogen fertilizer applications made to the appropriate varieties of wheat ensure a reliable supply of the increasingly wide range of flour required by European bakers. Protein content and protein quality are primarily determined genetically, but correct fertilization helps plants to use their genetic potential to the full. The quality of gluten, a protein fraction important for baking, deteriorates when wheat is undersupplied with nitrogen or sulphur.

With healthy diets in mind, many people are choosing to buy wholemeal bread, where all the grain is incorporated into the loaf. For this type of bread a high grain protein content of 14% is needed for the dough to be strong enough to allow the bread to rise.

Tin-baked bread needs flour with a protein content of about 12.5% to avoid cavities in the loaf, with French bread requiring approximately 11.5% and pitta bread needing a slightly lower level.

The great variety of cakes and pastries that are baked in Europe all require their own particular standards of flour, grown precisely with specific use of nitrogen.
The demand for pasta is met by growing Durum wheat, which is a hard wheat with a high protein level; here again management of nitrogen applications will modify the final protein content. A high proportion of the Durum wheat used is grown across southern Europe.

A deficiency of nitrogen can truly affect crop quality: In Denmark, for instance, due to strict national limitations on the use of nitrogen, the baking quality of Danish wheat deteriorated to such an extent that in 1999 farmers were no longer able to produce sufficient quality wheat for the domestic market. Formerly a quality wheat exporting country, Denmark became a net importer.

'Malting' barley for brewing and distilling requires quite different management, because a high yielding crop is required, but one with a low grain nitrogen content. As with wheat, specific varieties are grown, but the expertise of the farmer in growing the low-nitrogen grain required is essential to the production of a quality malt and non-cloudy beer.

**Other arable crops.**

Skilful use of nitrogen by farmers, both in deciding the quantities to apply and the timings of the different applications, are an essential part of growing quality produce. The wide variety of fresh potatoes now on offer are to a large extent the result of novel growing techniques and nitrogen management. Potatoes grown for storage over winter should have a low availability of soil nitrogen in the final stages of maturity, otherwise they will not store well and may have poor taste or develop black spots during cooking, particularly when potassium is deficient.

Similarly, the efficient production of sugar from sugar beet requires very exact nitrogen inputs. If the nitrogen content in the beet is too high at harvest time this can upset the precipitation of sugar during processing and thus reduce the sugar yield.

**Vegetables and salads.**

The market for fresh vegetables and salads is very quality-conscious, and the growing of the crops in this sector requires the most precise management of fertilizer inputs. Highly fertile soils are required for these short season crops and some, such as onions, often receive small precise applications of fertilizer when they are sown to ensure an even establishment and crop uniformity. Others, such as Brussels sprouts, are often supplied with special high-nitrogen solution fertilizers which are injected into the soil near the plant roots to ensure the continuing and steady supply of nitrogen, which is required for a quality harvest of most brassicae. Few of the appetising and nutritious vegetables the European consumer has come to expect would be available at high quality were it not for the expertise of the grower in the use of his nitrogen fertilizer. Vegetables grown with insufficient nitrogen tend to be more fibrous and less succulent, may be pale and appear 'undernourished'.

Although scientific assessment now disputes this (see page 47), ingestion of nitrate rich food is nevertheless considered a health risk. Vegetables are the main source of ingested nitrate and the EU regulation 194/97 and national regulations set limits for the nitrate content in fresh vegetables and processed baby food. Therefore crops with high nitrate contents at harvest time are just not marketable.
Vines and wine.
The quantity of nitrogen required for growing and fermenting the grapes is not large but it is significant in quality wine production. The seasonal requirements of the vine are mainly supplied from reserves in the roots to support leaf development. Leaves need adequate nitrogen for the synthesis of sugars, which are mobilised to the berries.

As mentioned earlier, nitrogen is a key component of amino acids and towards the end of ripening large quantities of free amino acids are transported to the berries. By harvest half of the nitrogen present in the whole plant is located in the berries.

A reduced shelf-life, known as ‘advanced aging’, of several white wines produced in Germany in the 1990s was subsequently attributed to a shortage of nitrogen in the growing vines. When only about two years old the taste of such wines had deteriorated so that they seemed much older and they soon became unpalatable.

Fermentation needs a high level of natural sugar but if nitrogen is deficient ‘Must’ fermentation can stall. The yeasts within the Must need nitrogen to grow and wine quality can be spoilt if the yeasts break down natural proteins to find their nitrogen. If the Must is low in nitrogen a yeast feed, usually containing ammonium nitrogen, is needed.

The total nitrogen required is not great but it is essential to allow the fermentation to progress well to produce highly palatable and enjoyable wine.

Livestock feeds.
The forage and cereals required for livestock feeds can ideally be produced on the same farm as the animals to be fed, and should provide the foundation of their diets. The quality of grass, both when grazed and when preserved as hay or silage for winter feeds, is significantly improved by the good management of the nitrogen fertilization, from manures and from mineral fertilizers. Forages such as grass can supply the majority of the energy and protein requirements of cattle and sheep. Together with cereals, other forages, particularly maize and certain brassicae, are also major contributors to the diets, and the nutritional quality of these feedstuffs relies on good fertilizer management.

The production of high quality feedstuffs is important economically for the farmer. For example, improving the protein content of quality silage from 12% to 15% made on one hectare of land in a year could save the import of half a tonne of protein feed onto the farm. This would only require an extra 40 to 50 kg of nitrogen to be taken up by the crop.

On livestock farms, where there is usually a good supply of manure, nitrogen fertilizers are used to supplement this source to ensure the efficient production of as much of the energy and protein supply for the livestock as can be achieved. Meat and other livestock products grown on farms using high levels of home-grown feeds is popular in the marketplace, the ready traceability of the basis of the diet adding further to the quality of the end-product.
Conclusion

The continuing and appropriate use of nitrogen fertilizer underpins life for the population of the world. Among some people in the developed world is the misconception that nitrogen fertilizer is an optional agricultural input, designed to make life easier and more profitable for the farmer. While it is clearly true that it is an essential input for profitable farming, it is also the prime essential input to ensuring a sustainable world food supply.

Norman Borlaug summed up the importance of fertilizer nitrogen in his speech accepting the Nobel Peace Prize in 1970:

"If the high-yielding dwarf wheat and rice varieties are the catalysts that have ignited The Green Revolution, then chemical fertilizer is the fuel that has powered its forward thrust..."
Sources, References and Bibliography.


