Nitrogen Management in Field Vegetables

A guide to efficient fertilisation

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Canada

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LANDWIRTSCHAFTSKAMMER
HANNOVER

NUTRITE

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Table of Contents

1 Introduction

Nitrogen is an element required for plant growth. It is an important component of proteins, enzymes and vitamins in plants, and is a central part of the essential photosynthetic molecule, chlorophyll. It is present in plant alkaloids and thousands of other substances of great social and economic importance in our society.

Plants absorb nitrogen in the form of nitrate ions (NO_3^-) and ammonium ions (NH_4^+) through their roots. The quantity of nitrogen absorbed by a plant depends on many variables, including the stage of plant growth, the concentration of other nutrients in the soil, the availability of soil water, and the weather conditions. Most crop plants take up nitrate in greater amounts than ammonium, and nitrate, unlike ammonium, accumulates in plant tissues when available nitrogen is greater than the amount required for optimal growth. While nitrate is easily leached from soils by percolating water, ammonium, with its positive charge, is held by the soil. During soil processes, ammonium is normally converted to nitrate.

Nitrogen is no more important to plant survival than any other essential element. However, it is required in much greater quantity than most other nutrients, so cropping practices often call for large applications of nitrogen fertiliser to maximise yields. The Green Revolution, which doubled world food production between 1950 and 1975, relied greatly on crops that were bred to achieve high yields when grown using intensive farming practices, including large amounts of nitrogen fertilisers.[1] By 1950, the annual world nitrogen fertiliser consumption was 4 million tonnes. In 1975, it had risen to 40 million tonnes.

In vegetable crops, the yield response to nitrogen is dramatic, and the cost of fertiliser is small compared with the cost of lost yield. Farmers often err on the side of over-application of nitrogen, rather than risk under-fertilising and suffering lost revenue. It is difficult to reconcile this practice with environmental responsibility. While water sources become polluted and ecological damage and health risks augment, the farmer does not want to shoulder the costs of sustainable production as lower yield and revenue from reduced fertiliser application. The consumer does not want to pay more for farm produce to offset such costs. How can the fertilisation of field vegetables be done in an environmentally sound way that allows both farmer and consumer to avoid personal investment in a clean environment?

One key to efficient fertilisation is to avoid over-fertilisation. A crop that is over-fertilised with nitrogen may be more susceptible to disease than those that are not[2], or may have elevated nitrate levels in vegetable tissues. Elevated nitrate levels influence the quality of vegetables in a variety of

What is the cost of over- or under-fertilising?

Suppose the cost of ammonium nitrate fertiliser (34-0-0) were $0.40 per kg. The cost of over-fertilising by 50 kg/ha of nitrogen would be close to $60.00 [50 kg/ha x 100 / 34 x $0.40]. The fertiliser saving of under-fertilising by 50 kg/ha would be close to $60.00, but the cost in the case of a cauliflower crop would be a 15% reduction in yield, corresponding to lost revenue of $1750.00!

ways; Brussels sprouts have been found to taste even more bitter (!) when over-fertilised with nitrogen[3] and to produce undesirable, elongated sprouts. Vitamin C levels in vegetables drop as nitrate level increases.[4,5] Over-fertilisation also causes water pollution by nitrate leaching. **Eutrophication** can result from nitrate pollution, causing devastating ecological effects, and high nitrate levels in drinking water may be harmful to human and animal health.

> **Eutrophication** is a natural process that occurs in bodies of water. Nutrients in the water, such as nitrogen, phosphorus fertilise the aquatic plant life. Plants grow and algae proliferate in what are known as blooms. As plants grow, some tissues age and die. As the number of plants and algae increase the quantity of this tissue or organic matter accumulates. Microbes use oxygen to break down the organic matter.
>
> When agricultural pollutants such as nitrogen and phosphorus enter the water, plants and algae grow more, and so the amount of organic matter accumulates quickly. So much oxygen is used up breaking down this material that the oxygen level of the water falls very low. Many plants and animals cannot survive with little oxygen so they die. Bodies of water that have undergone severe eutrophication are sometimes called "dead", because they support very little life.

The general public is concerned about nitrate in vegetables and in drinking water because of the potential health risk that was brought to light in the 1980s. Studies showed conclusively that nitrate mixes with amines to form carcinogenic compounds called nitrosamines. However, recent studies have found that nitrosamines are not formed during ingestion or digestion of nitrate rich vegetables, and that some minor benefits of eating nitrate-rich vegetables may exist.[6,7] Several epidemiological studies have been unable to confirm the link between ingested nitrate and cancer.[8,9,10,11] However, these studies have also not proven that there is no risk of cancer from eating nitrates. Until we can be certain that high nitrate levels in vegetables are safe, producers would be wise to grow vegetables containing low concentrations of nitrate. Efficient fertilisation achieves this goal, while reducing water pollution.

Some countries have introduced regulations to limit allowable nitrate in vegetables and in some cases have gone so far as to limit the total amount of nitrogen that can be applied to certain crops, in an effort to prevent over-fertilisation and its negative effects. These limits can sometimes mean that the farmer must under-fertilise.

Under-fertilisation (as demonstrated in the example) can be, depending on one's perspective, as undesirable as over-fertilisation. Not only is it costly in lost yield, but it may also result in a crop of poorer quality. Leafy greens such as spinach are more desirable to consumers when they are a rich, dark green. Under-fertilisation can yield pale, yellowed greens, brassicas with heads of undesirable shape[12] and vegetables bearing a host of other characteristics that may cause downgrading and the accompanying reduction in marketability and revenue.

Efficient nitrogen fertilisation of field vegetables is the ideal situation, in which the crop receives neither too little nor too much nitrogen. In Québec, some widely used approaches to determining fertilisation rates cannot be efficient. They are based on recommendations made according to average values of crop needs. They frequently result in the farmer applying the plant's entire uptake as fertiliser, ignoring the nitrogen already in the soil, in crop residues and irrigation water, and from a host of other sources. Equally ignored are the processes in the soil that compete with the crop for nitrogen. We generally think of crop needs as crop uptake. In reality, more nitrogen than the plant uptake up may be required for optimal growth, and should therefore be counted as crop needs. The more completely we account for nitrogen inputs and outputs in the cropping system, the more efficiently we will be able to fertilise.

This guide has been designed for the farmer and agricultural professional to use as a handbook of information on nitrogen fertilisation of field vegetables. Different methods for arriving at efficient fertilisation, according to the goals of the producer -- be they environmental sustainability, cost effectiveness or improved quality of produce -- are discussed, with detailed descriptions of how to estimate nitrogen inputs and outputs and calculate nitrogen balances. This guide presents some tools that can be used to evaluate the nitrogen status of the soil and plants. Because of the scarcity of information available on managing nitrate levels in vegetable tissues, this topic has been explored. Readers will notice that this guide often refers to German and Québecois studies, examples and situations. While the context is often limited to Québec and Germany, the concepts and principals are widely applicable throughout Europe and North America.

2 Nitrogen cycle

Plant growth depends on nutrient cycling through the environment. In reality, these complex cycles are not independent. The nitrogen cycle does not function without the phosphorus cycle, the carbon cycle and a host of other cycles of which plants play a primary role. However, in a discussion of nitrogen management in vegetable crop production, it is helpful to examine key aspects of the nitrogen cycle alone. In so doing, we can identify processes that contribute nitrogen to the soil for crop uptake and growth, or inputs, and process that remove nitrogen from availability to the plant, or outputs. By manipulating these inputs and outputs, we can change the balance of nitrogen in the soil. Managing nitrogen fertilisation efficiently means achieving equilibrium between the inputs and the outputs.

2.1 Inputs

We tend to think of cropping inputs as only those things that are actively applied to the soil, such as manure and fertiliser. In fact, nitrogen inputs come from other sources. Organic matter in the soil, for example, releases nitrogen. Managing nitrogen in vegetable crop production calls for an understanding of how these processes contribute to the soil-plant environment.

2.1.1 Soil mineral nitrogen in spring (SMNS)

Contrary to the commonly held view that the soil contains little or no mineral nitrogen in spring, it may contain a significant amount. This amount is a function of many factors, including the crop previously grown on the site, the fertilisation history, the amount of winter precipitation, the soil humus content, the soil texture and temperature.

Accounting for the spring soil mineral nitrogen (SMNS) input is more important in vegetable production than in many other cropping systems. Research shows that vegetable crops leave behind more mineral nitrogen for the next crop than cereal crops do, for example. A study carried out in Germany found that fields in which vegetables were continuously grown had higher levels of SMNS than those planted once in vegetables, followed by cereals, or continuous cereal crops (Figure 2). Figure 2 shows that the total nitrogen found in the fall in the top two meters of soil in a continuous vegetable cropping system was 765 kg N/ha. This figure seems very high, but in 1985, at the time this study was conducted, this concentration of nitrogen was typical of fields in which vegetables had been grown for many years using fertilisation recommendations that disregarded the SMNS.

The amount of nitrogen left in the soil in the fall is at risk of being leached out of the soil from precipitation in the fall and snow melt and rain in the springtime. Much leaching may have occurred by the time crops are planted in the spring, and the small root systems of seedlings or transplants are not able to take up much of the remaining nitrogen. By the time plant roots grow deep into the soil, the nitrogen in the lowest layers of the soil may have already been leached away. Shallow-rooted crops may never be able to take up nitrogen from deep in the soil profile.

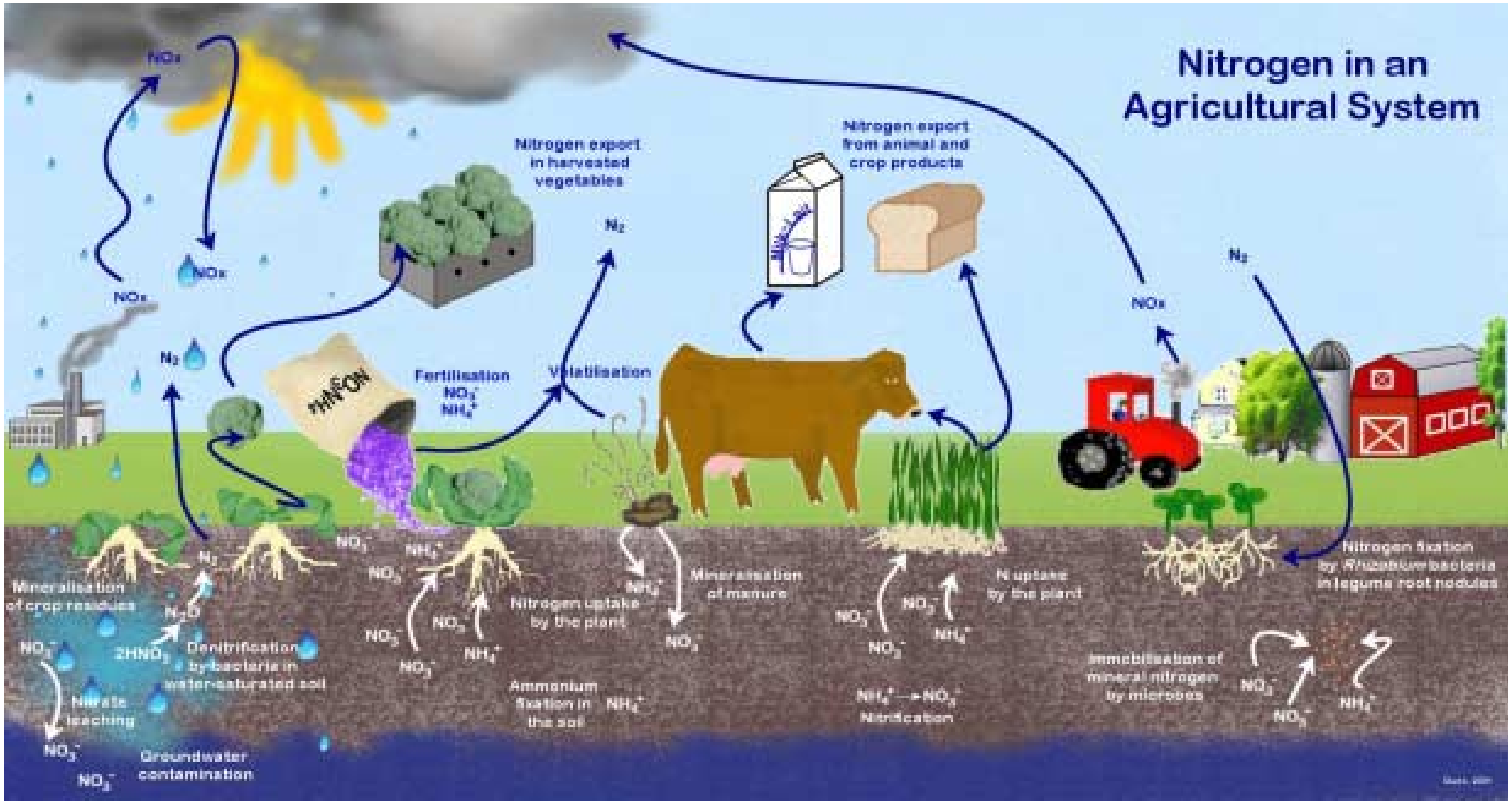
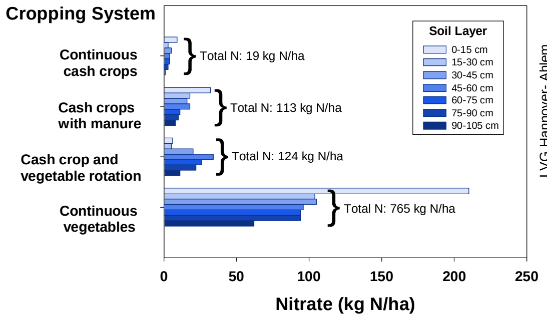


Figure 1: Nitrogen in an agricultural system

Figure 2

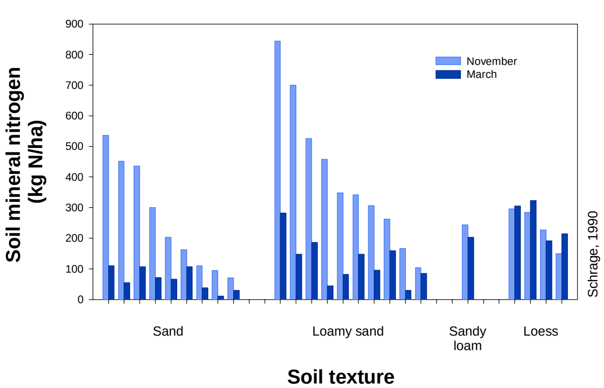
Soil nitrate measured in different soil layers in October for four different cropping systems



Soil texture also affects the amount of nitrogen available early in the season. Coarse soils have large pore spaces and less soil particle surface area. They are also characterised by a low field capacity, and fast drainage. Altogether, the effect is that water moves much more quickly through a coarse-textured soil than a fine-textured soil, carrying the nitrogen, in nitrate form (NO_3^-), along with it. Coarse-textured soils (sands and loamy sands) in a German study lost more nitrogen over the winter (November to March) than fine-textured soils did (Figure 3). Silty soils actually contained more nitrogen in spring than the previous fall because the amount of nitrogen mineralised exceeded the nitrogen lost through leaching.

Figure 3

Soil nitrogen content of vegetable fields of different soil textures in autumn and the following spring



In Canada, the winters are much colder than in Germany, and one might intuitively arrive at the conclusion that nitrogen does not change in soils during a long, cold, frozen period. In fact, research conducted in Alberta showed that mineral nitrogen increases while soil is frozen and decreases when it thaws (Table 1).[13] The net effect is that nitrogen mineralised in the fall and nitrified in frozen ground is denitrified in spring or lost to leaching Figure 4. In the Alberta studies conducted on cereal or fallow fields, the soil nitrate level did not really differ from fall to spring, although clearly gains and losses occurred throughout the winter and the thaw (Table 2). How do the large quantities of nitrogen-rich residues of vegetable crops affect nitrogen flux during winter and in the spring? Further research is required to answer this question.

2.1.2 Mineralisation of organic matter

Living things are organic, that is carbon-based. Soil always contains some organic matter from the remains of plants, microbes, fungi and even animals. Organic matter contains nitrogen, but it is bound in large molecules such as proteins, which are unavailable to plants. Mineralisation transforms this organic nitrogen into inorganic nitrogen (mineral) by microbial activity. Nitrate (NO_3^-) and ammonium (NH_4^+) are inorganic nitrogen forms and are the only forms that plants can absorb from the soil solution in significant quantities. Mineralisation occurs naturally near the surface of the soil, where conditions are conducive to microbial activity. Crop residues, green manures, compost,

Figure 4: Factors and processes influencing soil mineral nitrogen from fall to spring under Canadian winter conditions

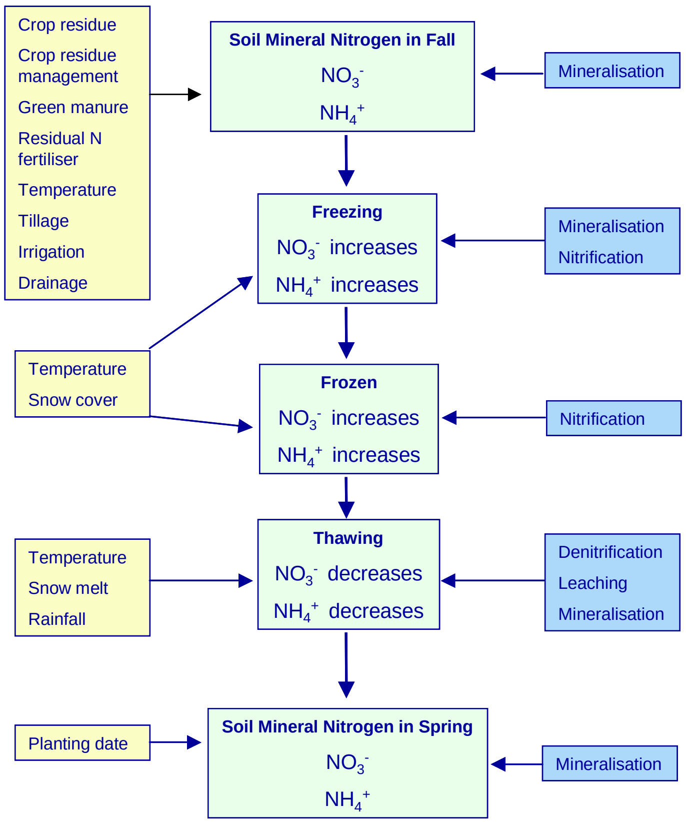


Table 1: Net change in mineral nitrogen content of soil during freezing, when frozen and after thaw in Alberta.

Mineral nitrogen (kg N/ha)						
Soil layer	Net change					
	Freezing period		Frozen period		Thaw period	
(cm)	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N
0-60	20	28	14	14	-22	-17
0-120	24	31	14	17	-23	-21

Adapted from Malhi and Nyborg, 1986

Table 2: Nitrate-nitrogen content of soil during the winter following cereal production or summer fallow in Alberta

Nitrate-N content of soil (kg N/ha)				
Soil layer (cm)	**Fall sampling before freezing**	**Sampling of frozen soil**	**Last sampling before thaw**	**Sampling after thaw**
Fields with crop stubble (six sites)				
0-30	17	31	39	23
30-60	8	9	13	9
60-90	4	5	6	5
90-120	3	3	4	3
0-120	**32**	**48**	**62**	**40**
Fallow fields (two sites)				
0-30	50	62	89	48
30-60	14	16	19	16
60-90	12	12	12	12
90-120	6	6	6	8
0-120	**82**	**96**	**126**	**82**

Adapted from Malhi and Nyborg, 1986

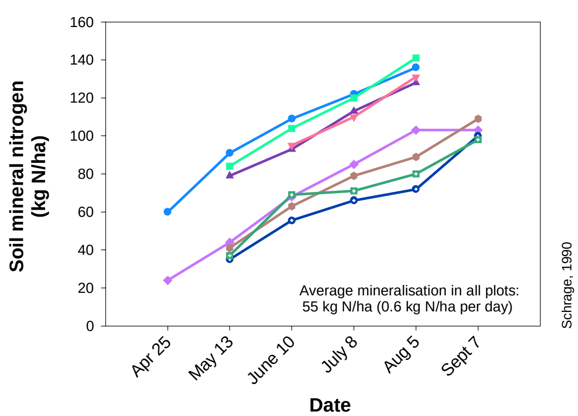
manure and other types of organic fertilisers also supply growing crops with nitrogen through mineralisation.

Humus

Soil organic matter is made up of several components, including fresh, easily degradable organic matter, as well as humus. The term "humus" refers to a number of stable components that are more resistant to mineralisation than fresh organic matter because they have already undergone some mineralisation and contain very little nitrogen. Despite its resistant nature, humus liberates a small, but steady amount of mineral nitrogen. In Germany, measurements of nitrogen released by humus between April and September were made in soils of fallow fields protected by shelters 50 cm above the ground (Figure 5). Fresh organic matter was absent from the soil surface of the fallow land, and the shelter prevented losses of nitrate by percolation of water from precipitation. Under these conditions, the nitrogen measured must have come from mineralisation of humus in the soil, and the cumulative effect demonstrated that the nitrogen was released throughout the season. Differences in the rate of nitrogen evolution may be explained by variations in humus content, temperature, moisture, and the bulk density and other characteristics of the soils. Mineralisation is favoured by adequate moisture and oxygen, and by warm temperatures.

Figure 5

Cumulative nitrogen from mineralisation measured in fallow plots in vegetable fields



In Western Europe, the average mineralisation rate is about 5 kg N/ha per week in vegetable fields containing 2 to 4% soil organic matter.[14, 15] This value was determined from many studies on different soils and under diverse field conditions.

In Québec, some agronomists use a rule of thumb to calculate the amount of nitrogen released by mineralisation of soil organic matter. The rule considers that 15 kg N/ha of nitrogen is released during the growing season for every one percent soil organic matter. Thus a soil with 5.5 % organic matter releases (5.5 x 15) 82.5 kg N/ha over the course of the season. This rule is used to modify the standard recommendations set forth in the CPVQ grilles de fertilisation.[16] These recommendations assume that the soil contains, on average, 4% organic matter, and already take into consideration the mineralisation from this 4% soil organic matter. Therefore, when making fertiliser recommendations, agronomists in the province credit only the 15 kg N/ha for each one percent above the average of 4%.

There are several drawbacks to this rule of thumb. For example, it assumes that the more soil organic matter, the more mineralisation occurs. In reality, very high soil organic matter content may be indicative of soil compaction or poor drainage, both of which may reduce mineralisation rates. In addition, the rule does not take into account differences in growing season across Québec. Finally, the rule was designed to work with the CPVQ grilles de fertilisation, and may not be well suited to calculating nitrogen fertiliser recommendations using methods such as the nitrogen balance sheet. The 5 kg N/ha per week estimate from extensive studies in many conditions appears to be more useful, and is easily adaptable to growing seasons of different lengths.

Sources of organic matter

Application or incorporation of crop residues, green manure, compost, solid manure and organic fertilisers supplies crops with nitrogen as these organic materials mineralise. Crop residues and green manures represent the largest potential source of mineral nitrogen in the vegetable cropping system with the exception of chemical fertilisers.

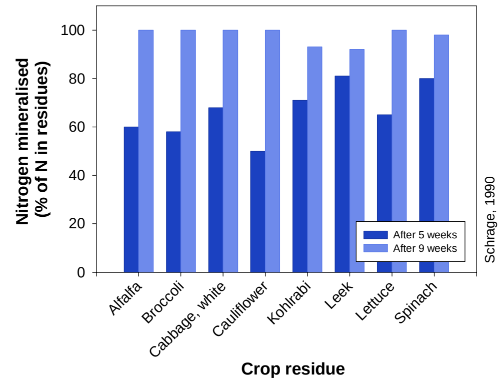
Crop residues and green manures

Fresh crop residues and green manures (crops grown expressly to be incorporated into the soil for organic matter) decompose very quickly if the soil temperature is sufficiently high. Under normal summer weather conditions, 70% of the nitrogen present in organic form in crop residues becomes available for absorption by the next crop for a period of 10 weeks following incorporation. However, the amount of nitrogen that mineralises and the timeframe over which mineralisation occurs can vary significantly.

In a study conducted in Western Europe, over 80% of the mineral nitrogen present in crop residues was released as early as 9 weeks after incorporation (Figure 6). It is important to note that the high rates of mineralisation in this study were due to exceptionally good conditions; the soil was warm, moist and very well aerated.

Figure 6

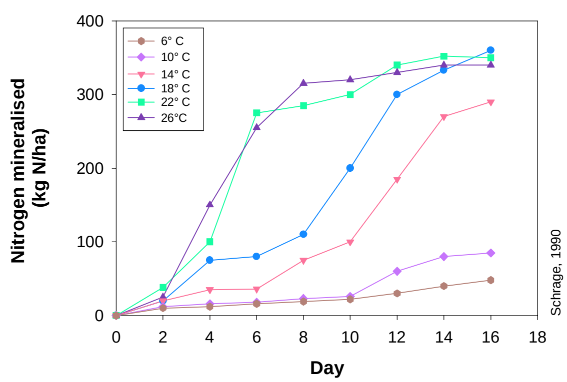
Mineralisation of nitrogen from vegetable crop residues after five and nine weeks of incubation



Warm temperatures favour microbial populations. A study demonstrated the effect of temperature on the release of mineral nitrogen from crop residues by incubating the equivalent of 359 kg N/ha in the form of cauliflower leaves in soil (Figure 7). The higher the temperature, the more quickly mineralisation occurred. This study was conducted as an incubation experiment, under very controlled moisture and aeration conditions. In the field, fluctuations in moisture, aeration and other factors

Figure 7

Cumulative quantity of nitrogen released by mineralisation of cauliflower residues at different temperatures



* The total N content of the leaves incubated at each temperature was 360 kg N.

mitigate the effect of temperature and mineralisation occurs much more slowly.

Incorporation also enhances mineralisation by bringing the soil microbes into direct contact with the residues, and the size of residue particles also plays a role. Residues that are finely chopped have greater surface area exposed to microbial action and therefore breakdown more quickly than larger pieces.

Nevertheless, differences in mineralisation rates of residues of different crops are influenced to a greater degree by the composition of the tissues themselves. The ratio of carbon to nitrogen is important; tissues containing a higher carbon to nitrogen ration (more carbon) are more resistant to mineralisation. Other aspects of the chemical composition of the tissues play a role as well. One study of finely and coarsely chopped vegetable crop residues revealed that crops, such as spinach, which contained relatively small percentages of lignin and hemi-cellulose, mineralised faster than crops with higher percentages of these components. These substances are carbon compounds that make up the cell walls, and they are very resistant to microbial action.[17]

Crop residues and green manures can release significant amounts of nitrogen. The amount depends on the composition of the residue and the environmental factors that influence mineralisation rate. Method of managing the fresh organic matter, be it crop residue or green manure is a primary factor in whether the mineralised nitrogen is used by a subsequent crop or lost to deeper layers of the soil and the groundwater.

In a study conducted in Québec, cauliflower and red cabbage residues were managed using four methods: the residues were removed from the field (control); incorporated in fall; left on the surface in fall; or incorporated in spring.[18] A crop of wheat was then planted on all sites. The residues contributed between 10 and 30% (6 and 18 kg N/ha) of their original nitrogen to the growth of the wheat crop. The fall incorporation method was the most consistent in contributing significant amounts of nitrogen to the wheat crop, but both fall methods also resulted in significant leaching losses, whereas the spring incorporation method did not.

Crop residues may contribute in excess of 100 kg or mineral nitrogen per ha (Table 3). Most crop plant species supply an average of 3 kg of mineral nitrogen per tonne of fresh biomass (plant tissue). Because of their symbiotic relationship with nitrogen fixing *Rhizobium* bacteria, legumes release more mineral nitrogen than other crops when they decompose--an average of 5 kg/tonne of fresh biomass.

Compost

Compost generally supplies less mineral nitrogen, proportionately, than crop residues and green manures. During the composting process, the easily degraded fresh material breaks down. Some of the nitrogen is volatalised, and the organic matter that remains is relatively resistant to mineralisation. However, compost contains a small quantity of mineral nitrogen, which is immediately available to plants.

Table 3: Potential nitrogen mineralisation from crop residues

Crop	Fresh biomass normally incorporated after harvest (t/ha)	Potential nitrogen from mineralisation (kg/ha)
Brussels sprouts	50-60	150-200
Cabbage, red Cabbage, white (processing)	40-50	120-150
Broccoli Cabbage, Chinese Cabbage, Savoy Cabbage, white (fresh) Cauliflower Fennel Peas	30-40	90-120
Beans Carrots Celery Lettuce, iceberg	20-30	60-90
Kohlrabi Leeks Spinach	10-20	30-90
Corn salad Lettuce Radish, red Radish, white	< 10	< 30

Scharpf, 1991

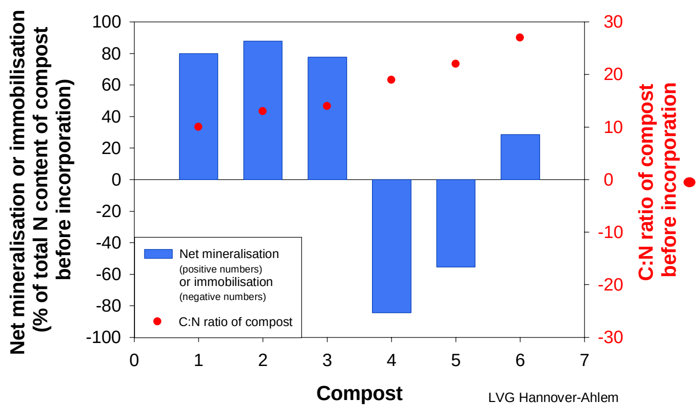
In a field trial, different composts were applied to different plots. In each case, the researchers applied the quantity of compost that contained a total of 150 kg N/ha. A crop of ray grass was planted in the compost-amended soil. No additional nitrogen fertiliser was applied. In some of the plots, soil nitrogen from mineralisation of the compost increased (Figure 8). In others the microorganisms immobilised more nitrogen than was released during mineralisation (Compost 3 and 4). Immobilisation is greatly affected by the carbon to nitrogen ratio of the compost. The composts with low C:N released the greatest quantities of mineralised nitrogen. The application of compost often contributes little mineral nitrogen and may even result in the immobilisation of soil nitrogen to the detriment of the crop. However, applying compost year after year indirectly enhances the supply of organic nitrogen by increasing the soil's humus content, improving soil structure and creating conditions favourable to microbial activity. The nitrogen content of compost can be assessed through laboratory testing.

Manure

Manure is an excellent organic amendment in crop production. It contains nitrogen in both mineral and organic form, and contains many other nutrients as well. Manure management is

Figure 8

Net mineralisation or immobilisation of nitrogen from composts of different C:N ratios during the season following incorporation, expressed as a percentage of total nitrogen content of composts of different C:N ratios



a highly complex science; manures of different kinds have different compositions, and factors such as method of storage, duration of storage and method of application all influence the composition.

Manure has been identified in Québec and elsewhere, as a poorly managed resource. It contains a wealth of plant nutrients, yet it is often regarded as a by-product of animal production, a waste material simply to be gotten rid of. When applied incorrectly, the benefit of manure as fertiliser is often overlooked, and the nutrients it contains often end up in ditches, watercourses and groundwater. Regulations such as the Regulation on the Reduction of Pollution from Agricultural Sources (RRPAS) requires that manure be handled in ways that minimise pollution, particularly nitrate and phosphorus pollution of groundwaters.[19] To this end, the RRPAS sets limits on the amount of manure that may be safely applied to cropland based on the nitrogen content of the manure. The extent of the vast field of manure management is beyond the scope of this guide, but certain points should be considered.

The nitrogen content of manure can be estimated from standard tables.[20] The values from tables may not, however, accurately reflect the composition of the manure in question. The nitrogen content can vary considerably according to animal husbandry practices, including differences in nutritional rations, bedding and manure storage. It may be preferable to have a sample of the manure analysed. Protocols are available that describe proper methods of manure sampling.[21] In Québec, the amount of nitrogen is then calculated taking into account various factors by using indices. Tables of indices and methods of calculation are available in several guides.[16, 21]

Up to 50% of the nitrogen present in liquid manures and poultry manure is in the form of ammonium and therefore rapidly available to plants. The rate of mineralisation of the organic nitrogen, which is held in the solid particles of liquid and semi-liquid (slurry) manures, and make up a large percentage of solid manures, is comparable to that of organic nitrogen from compost.

Other organic fertilisers

Other types of organic fertilisers, such as feathers, meat, crab, fish, cottonseed meal and dried whey, are used primarily by organic farmers. These materials caused increases of 57% to 83% in the dry weights of plants relative to unfertilised plants in one study.[22] However, because the compositions of these materials are complex and varied, it is difficult to compare their effectiveness one to another or to mineral fertilisers. Are growth effects when fertilising with these materials due to the availability of nitrogen? Other minerals in these materials may well cause the effects. The rate of nitrogen mineralisation of these materials is generally slower than that of synthetic fertilisers, but the rate can vary significantly depending on the characteristics of the product. For example, one study on feathers as fertiliser showed that almost twice the amount of nitrogen was released from feathers in half the time when the feathers were ground to 0.5-mm instead of 1.0-mm particles. Microbial hydrolysis turned the same feather particles into a slow-release fertiliser.[23]

2.1.3 Precipitation

Nitrogen oxides (NO_x) generated by the use of fossil fuels by motor vehicles, by the energy production sectors and by various other activities enter the air. These nitrogen oxides are converted to nitric acid in the atmosphere before reaching the ground in the form of precipitation, gases and acid dust. In the National Atmospheric Deposition Program in the U.S. has measured the annual nitrogen input from wet deposition, or precipitation. The nitrogen, in the form of ammonia, ammonium and nitrate, varies between less than 1 kg N/ha and 7 kg N/ ha annually.[24] In Europe, nitrogen in precipitation can be far greater; the population is much denser than in most of North America, and therefore the amount of nitrogen entering the atmosphere from fossil fuel burning by individual and industrial users is higher. The concentration of nitrogen in rain has increased in Germany over the past 50 years from 25 to 40 kg N/ha. In Lower Saxony, intensive animal production has caused the concentration to climb as high as 120 kg N/ha because of the ammonia volatilised from manure.[25]

2.1.4 Irrigation

Irrigation water may contain a significant amount of nitrogen, particularly in areas of high density of animal production. Irrigation water should be analysed regularly to obtain an estimate of the nitrogen input from this source.

Example of how to calculate the N input from irrigation:

Irrigation at a rate of 20 L/m^2 with water from an artesian well in which the nitrate concentration is 50 mg/L, supplies the soil with the equivalent of 10 kg /ha of nitrate (calculation: 20 L/m^2 x 50 mg/L x 10 000 m^2/ha x 1 kg / 1 000 000 mg). If irrigation is repeated 10 times throughout the season, the total input is 100 kg/ha of nitrate, of which 22.6 % (or in this case 22.6 kg) is nitrogen, an amount that warrants consideration in the nitrogen balance.

2.1.5 Mineral fertilisation

Crop plants require nitrogen in very large quantities. The amount available from natural sources (soil processes, organic matter, irrigation etc.) is often not sufficient to meet crop needs, and so the remainder must be applied as fertiliser. The nitrogen balance can be used to calculate the amount of fertiliser to apply. The difference by which outputs exceed the natural inputs described above, corresponds to the amount of fertiliser that should be applied.

Many kinds of nitrogen fertiliser are available on the market. They differ in composition (ammonium, nitrate, urea), concentration, rate of release, price and presence and availability of other nutrients or contaminants. Different forms are available (solid, liquid, gas) and may require different methods to safely and effectively apply them. All of these factors influence the choice of fertiliser.

2.2 Outputs

2.2.1 Plant needs

The quantitative nitrogen requirements of vegetable crops consist of: 1) the amount of nitrogen that will actually be taken up by the plant and integrated into its biomass, and 2) a quantity of nitrogen that must nevertheless be present in the soil in order for the crop to achieve its full potential yield (safety margin). The addition of these requirements gives the value of the overall plant nitrogen needs.

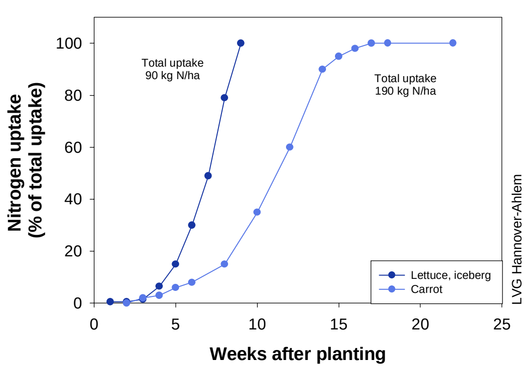
Uptake

Several factors affect the rate and amount of nitrogen uptake by crop plants. Nitrogen uptake is enhanced by a warm, sunny climate because photosynthesis rates are high under these conditions. Certain crops, and certain cultivars in particular, grow more rapidly or to a larger size than others and therefore take up nitrogen at a faster rate or in greater quantity from the soil. A plant's nitrogen requirements also differ according to its growth stage. While a plant's nitrogen requirement when it is small is low (Figure 9), the nitrogen supply at this time is critically important. In many crops, a delay in growth caused by a lack of nitrogen leads to irreversible yield reduction.[26] Other crops may recover, but maturity may also be delayed; this may pose a problem if the timing of harvest is critical.

Plant nitrogen uptake, or nitrogen content, is the amount of nitrogen present in the fresh biomass. It is primarily in organic form and includes the nitrogen in the root system, which corresponds to approximately 10% of the plant's aerial weight (more in the case of root and tuber vegetables). Table 4 contains the total nitrogen uptake of various vegetable crops. If yield differs significantly from these averages, the nitrogen content value can be adjusted accordingly using a ratio calculation.

Figure 9

Nitrogen uptake of two vegetable crops



Safety margin

While the nitrogen content of the plant represents a certain amount of nitrogen needed to produce biomass, it does not, on its own, fully reflect the general nitrogen "needs" of the plant. In fact, for optimal growth, the plant requires additional nitrogen to be present in the soil, even though this nitrogen normally not absorbed. This additional amount is called the safety margin.

The safety margin for a crop is determined experimentally as the quantity of mineral nitrogen that is present in the soil at harvest when optimal yield is obtained. Studies showed that the safety margin was more

Table 4: Approximate nitrogen uptake per tonne of yield of common vegetable crops, and the nitrogen uptake for a crop of average yield

Crop	Approximate nitrogen uptake per tonne of yield (kg N/ha)	Average yield (t/ha)	Nitrogen uptake for average yield (kg N/ha)
Beans, bush	8	12	100
Beets	5	50	250
Broccoli	13	20	260
Brussels sprouts	16	25	400
Cabbage, Chinese	3.5	70	250
Cabbage, white (early)	4	40	160
Cabbage, white (late)	3.5	80	280
Carrots	2.5	60	160
Cauliflower	7.5	35	260
Celery	4	50	200
Corn salad	4	15	60
Endive	3	40	120
Kale	5	30	150
Kohlrabi	4.5	40	180
Leeks	3.5	40	140
Lettuce, Boston	2.5	40	100
Onions	2.5	60	150
Peas	30	4	120
Radishes	3.2	25	80
Spinach	5	25	120

Scharpf, 1991

or less constant, and that reducing it caused yields to diminish despite the continued presence of enough nitrogen in the soil to cover the optimal yield uptake of nitrogen by the crop. Thus the safety margin is required for optimal yield, but is not taken up.

One role of the safety margin is to prevent nitrogen shortage that might occur if only the amount of nitrogen required for uptake were present in the soil. In such a case, excessive precipitation could cause a nitrogen shortage by leaching away some of the nitrogen needed for uptake. Aside from this risk-buffering capacity, the safety margin also allows the plant to extract its full quotient of nitrogen from the soil. Below a critical concentration of soil nitrogen, represented by the safety margin (Table 5), a plant's efficiency at extracting soil nitrogen is diminished.

Crops that have small, shallow roots, with few root hairs (leeks and onions), are inefficient at extracting nitrogen so the safety margin provided must be relatively large. Conversely, plants with long, deep, extensive root systems, and long cropping duration require only a small safety margin.

The safety margin must be kept as small as possible while still allowing maximum growth. A crop of cauliflower in one study continued to respond positively to added nitrogen until 370 kg N /ha had been applied (Figure 10). The fact that yield did not increase with further application suggested that the sum of nitrogen in the soil and the nitrogen applied filled not only the nitrogen requirement for uptake, but also the safety margin. Additional fertilisation only served to increase nitrogen residue in the soil that was

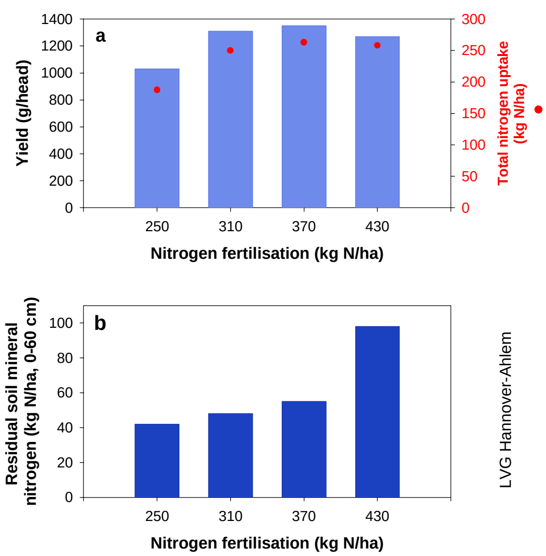
Table 5: Safety margin of nitrogen required for some vegetable crops

Mineral nitrogen required in rooted soil layer until harvest (Safety margin)		
< 30 kg N/ha	30 to 60 kg N/ha	60-90 kg N/ha
Brussels sprouts Cabbage, late Carrots, late	Beans Beets Broccoli, late Cabbage, Chinese Cabbage, early Carrots, early Celery Endive Kale, curly Kohlrabi Lettuce, head Lettuce, iceberg Radicchio Radish	Broccoli, early Cauliflower Leek Onion Spinach

Adapted from Scharpf, 1991

Figure 10

Effect of nitrogen fertilisation on
a) cauliflower yield and nitrogen uptake and
b) soil mineral nitrogen at harvest



susceptible to leaching. Deciding to add additional fertiliser to provide extra security would be inefficient, ineffective and environmentally irresponsible.

To prevent leaching of nitrogen after harvesting and potential contamination of groundwater, the nitrogen used for the safety margin can be removed from the soil by growing a cover crop of another species, such as radishes or mustard, which are excellent nitrogen scavengers.[27]

2.2.2 Mineral nitrogen not absorbed by the plant

Even under the best conditions, plants are able to absorb only 60 to 80% of the nitrogen applied in fertiliser. The remainder becomes unavailable to plants through various processes: leaching, denitrification, immobilisation, ammonium fixation, and volatilisation. In many cropping systems, nitrogen losses are primarily due to leaching and denitrification.[28] In fact, the U.S. Environmental Protection Agency estimates that fertilisers use contributes over 60% of total ammonia emissions to the atmosphere in the United States, or more than 500 million tonnes annually.[24]

Leaching

Leaching is a phenomenon that occurs primarily in the fall and spring when precipitation is abundant. Nitrate is soluble and completely free to move with the water. Infiltrating water carries the nitrate beyond the zone tapped by the roots and it eventually mixes with groundwater. Fall rains, and snowmelt in early spring alter nitrogen distribution considerably. In one study total soil mineral nitrogen content in the top 60 cm, the soil zone exploited by most vegetable crop plants, dropped from 125 to 33 kg/ha over the course of the winter. The nitrogen moved into the deeper layers of the soil (90-120 cm), where it was highly susceptible to leaching and largely unavailable to plant roots (Figure 11). Leaching is relatively uncommon during the summer because precipitation

Figure 11

Nitrogen movement through the soil over winter

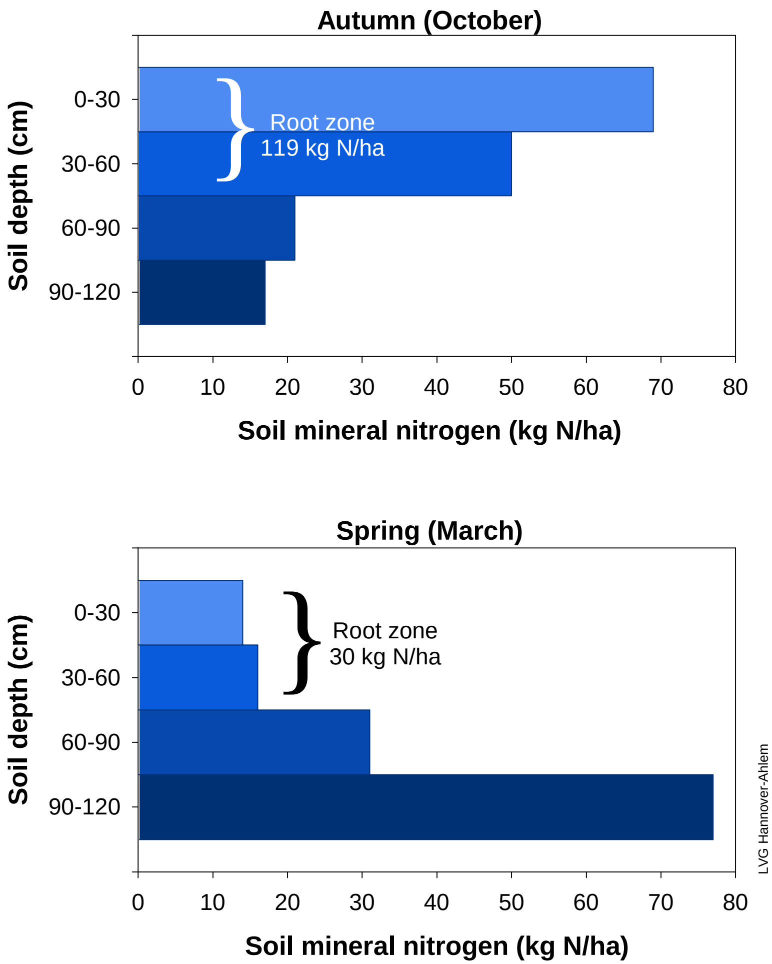


Figure 12: Relative displacement of soil nitrate when 30 mm of precipitation falls on soil saturated with water

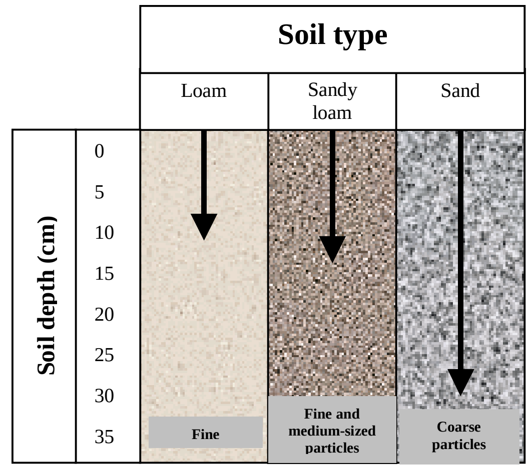
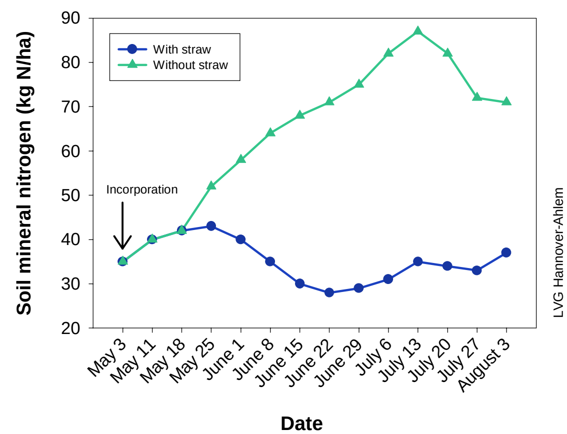


Figure 13

Effect of incorporating chopped straw (10 t/ha) on the soil mineral nitrogen concentration



is low and evapotranspiration rates are elevated; any water rapidly evaporates from the soil surface or is taken up by the plants, evaporating off of the leaves. Leaching can be significant in summer during times of heavy rain.

The quantity of nitrate leached depends on four main factors: the amount of precipitation/irrigation, the concentration of nitrate in the soil, the soil characteristics and the distribution of plant roots. The probability of leaching increases with the amount of precipitation and with the concentration of nitrate in the soil. Field capacity is the maximum amount of water that a soil can hold without percolation. When field capacity has been reached any additional water flows downward, bringing the nitrate with it. The texture of the soil is related to field capacity; coarse-textured soils have large pore spaces through which water flows easily, and therefore have low field capacity. Fine-textured soils have higher field capacities. For this reason, light soils (sandy) are more susceptible to nitrate leaching than heavy soils (clay) (Figure 12, Table 6).

Table 6: Relationship between soil texture, field capacity and probability of nitrate leaching

Soil type	Field capacity (mm of water per m of soil depth)	Probability of leaching
Sand	135	High
Loamy sand	210	↓
Sandy loam	245	
Loam	360	
Silty loam	330	
Clay	400	Low

Root distribution also influences leaching. Leaching of broadcast nitrogen is a greater risk in interrow soil zones. When transplants are small, the interrow area is large, and the nitrogen in this area is particularly susceptible to leaching because precipitation tends to be great in springtime. The interrow soil zone may remain large throughout the season in crops that have small root systems.[29]

Immobilisation

In the process of breaking down organic matter, microorganisms use nitrogen. If the organic matter that they work on does not contain enough nitrogen to supply their requirements, the microorganisms absorb mineral nitrogen from the soil. This nitrogen is converted to organic compounds inside the microorganisms and is not available for plant growth. This conversion of mineral nitrogen to organic nitrogen is called immobilisation.

Immobilisation becomes particularly intense when the carbon to nitrogen ratio (C:N) in the organic matter exceeds 30, indicating a great amount of carbon compared to nitrogen. Straw, sawdust, other woody materials, and some industrial by-products contain large amounts of carbon that when incorporated can raise the soil C:N considerably. In one study, adding straw resulted in lower soil mineral nitrogen levels than when straw was not added; the nitrogen was immobilised in organic form instead (Figure 13). Immobilisation is often a temporary phenomenon. The microorganisms eventually release the nitrogen back to the soil as metabolic wastes and as dead cells. In some cases, nitrogen fertiliser may be required so that the micro-organisms can break down the carbon in organic matter without depriving plants of nitrogen while the process occurs.

Immobilisation also happens when fertiliser is applied to the surface of the soil and remains unincorporated. The microorganisms involved retain the nitrogen for a period of two to five weeks before returning it to the soil in the form of mineral nitrogen. This form of immobilisation occurs under sunny rather than cloudy conditions. One explanation may be that because the surface of the soil dries under sunny conditions, that immobilisation cannot occur because the microorganisms are not able to function. The soil may remain quite moist beneath the dry surface dry layer.

As a general rule, during the growing season, microorganisms immobilise approximately 15 to 20% of mineral nitrogen input incorporated or present in the upper soil layer. If levels of mineral nitrogen in the soil are very high, immobilisation can remove up to 40% of the nitrogen that theoretically would have been available to the crop.

Denitrification

Most bacteria require exposure to air containing oxygen in order to function, but denitrifying bacteria are able to scavenge oxygen from nitrate (NO_3^-) in the soil when such conditions do not exist. It is this scavenging process that converts soil nitrate to the gases di-nitrogen (N_2) and nitrous oxide (N_2O) in the process of denitrification. The process occurs in oxygen-deprived soils such as marshes, peaty soils, and poorly drained ground and is favoured by high temperatures (> 15°C).

Denitrification rates are influenced by factors such as drainage, irrigation, precipitation, soil texture and structure, compaction, temperature, and fertilisation. A review of many denitrification studies revealed that denitrification is greatest in nitrogen-fertilised, irrigated soils (Table 7). In general, 10 to 30% of applied mineral nitrogen is subject to denitrification.

In Europe, scientists conducted studies on vegetable fields. Under regular cropping practices with incorporated crop residues and high nitrogen fertilisation, denitrification was typically between 30 and 40 kg N/ha. Annual nitrogen losses from denitrification may be as high as 100 to 200 kg N per hectare under typical vegetable crop field conditions.[25]

Nitrification

Microorganisms also carry out the process of nitrification. This two-step process begins with the oxidation of ammonia to nitrite, and is completed by the oxidation of nitrite to nitrate. This can contribute to leaching if ammonia fertiliser is converted primarily to nitrate through this process, instead of to ammonium, which binds to clay particles in the soil.

Table 7: The range of denitrification rates and mean denitrification rates in different agricultural systems

Agricultural system	Range of denitrification rates (kg N/ha per year)	Mean denitrification rate (kg N/ha per year)
Unfertilised, not irrigated	0-17	3
N-fertilised, not irrigated	0-110	13
N-fertilised, irrigated	49-239	113

Adapted from Barton et al., 1999

Ammonium (NH_4^+) fixation

Crops may be deprived of mineral nitrogen over the short term because of ammonium fixation. The process depends on soil texture; clay particles trap ammonium between their layers, making it unavailable to crops and placing it out of reach of microbes that are able to convert it to nitrate. This ammonium may become available later in the season. The agricultural impact of the process is not known, but it may be to blame when ammonium is less available than expected at the time of fertiliser application.

NH_3 volatilisation

The process by which ammonium (NH_4^+) is converted to ammonia (NH_3) is known as **volatilisation**. If this phenomenon occurs at or near the surface of the soil, ammonia, a gas, is released into the atmosphere and contributes to the greenhouse effect. Ammonium coverts readily to ammonia under certain conditions: high soil and air temperatures, dry weather. The likelihood that ammonium will be converted to ammonia rises exponentially with increasing pH, so ammonium fertilisers should be avoided when the soil pH exceeds 7.0. [30]

Under ideal conditions for volatilisation, up to 50% of the nitrogen applied may be lost to this process. To be effectively carried into the soil, ammonium must be quickly dissolved in soil water. This is best accomplished by incorporating the ammonium into moist, cool soil. If conditions favour volatilisation, fertilisers that contain a high concentration of ammonium (urea, manure) should be avoided.

Volatilisation costs!!!

Urea (46-0-0) is a commonly used source of nitrogen. Per kg of fertiliser, urea is comparable in price to ammonium nitrate (34-0-0), at about $0.43. But the concentration of nitrogen in urea is 35% greater than in ammonium nitrate, so per kg of nitrogen, urea is 35% less expensive (about $0.38).

If urea were applied at 100 kg/ha as a side-dress application mid-season, during hot, dry, windy weather, perhaps 40% of the nitrogen would volatilise. The application would cost $43/ha (100 kg x $0.43). However, instead of 46 kg of N (46% N in urea x 100 kg), the crop would receive only 18.5 kg N/ha (46 kg/ha x 40%) and the farmer would directly lose the equivalent of $11.20/ha ($0.28 x 100 kg x 40%) of nitrogen to the atmosphere.

If ammonium nitrate were used instead, which is more resistant to volatilisation, 135 kg/ha of fertiliser would be required to supply 46 kg N/ha, which would cost $58/ha (135 kg/ha x $0.43). The cost of applying just 18.5 kg N/ha using ammonium nitrate would be $23.40/ha (18.5 kg x 100 / 34 x $0.43).

3 Methods of estimating the nitrogen fertiliser requirements of vegetable crops

The quantity of nitrogen fertiliser to be applied is primarily a function of the difference between the mineral nitrogen content of the soil plus the amount expected to be released during the season from organic sources, and the nitrogen required by the plant. Before

3.1 Methods based on experience and observations

3.1.1 Experience

Some farmers rely very heavily on experience when deciding how much nitrogen to apply. In extreme cases, they feel that if they have obtained good yields in the past by applying very high levels of nitrogen, that they should continue to apply the same high level each and every year, irrespective of other factors. Other farmers modify this approach somewhat, and may temper recommendations according to the state of the soil, the previous crop, and other conditions. When trying to fertilise efficiently, it is wise to consider the conditions and characteristics of each field, and the year-to-year variation as well.

Single recommendation

Several guides make single recommendations for a given crop, regardless of the condition of the soil or the history of the field. In Québec for example, the *Conseil des Production Végétales du Québec* (CPVQ) and as the

applying fertilisers, it is important to measure or estimate these two main sources of mineral nitrogen in the soil: the nitrogen already available at the beginning of the season (called soil mineral nitrogen, or SMN) and the nitrogen released by mineralisation throughout the season. Vegetable producers may estimate nitrogen quantities on the basis of their experience and observations, by performing calculations, or by directly measuring the quantities involved by means of soil and plant analyses.

Québec Fertiliser Manufacturers Association each publish a guide for this purpose. Many other countries, states, or provinces prepare or endorse comparable guides. Because these guides are general, farmers can use their own experience to tailor the recommendations using correction factors.

Correction factors

Fertiliser N may be reduced where:

- A large quantity of crop residue was left behind the previous fall;
- The previous winter was mild and dry;
- The date of planting is late in the season;
- Fresh crop residues or solid manure were applied before planting;
- A below average yield is expected;
- The nitrate content of the edible part of the plant must be limited;
- The nutritive quality of the plant (sugar or vitamin C content) must be improved;
- Better disease resistance is required;
- The plant’s leaves are not the marketable vegetable product.

Fertiliser N may be increased where:
- Precipitation during the previous winter was heavy;
- Precipitation during the spring was heavy;
- Precipitation came late in the growing season;
- The date of planting is early in the growing;
- An above-average yield is desired;
- The plant's leaves must be maintained in good health (e.g.: carrots);
- A dark green colour is desirable.

The use of mulch in cropping practices has no specific effect on nitrogen requirements and does not change recommendations of quantity of N fertiliser to apply.

3.1.2 Observation

Plant colour

Farmers in Québec sometimes judge the need for nitrogen fertiliser by "eyeballing" the colour of the crop foliage. If the crop appears to be pale, they add more nitrogen. While this sometimes has the desired effect, it is not an efficient way of fertilising, and the farmer may well apply far more nitrogen than is needed. A variation has been used in some crops, which takes some of the guesswork out of the method: comparing the crop colour to a colour chart that has been developed for the given crop in the local area.

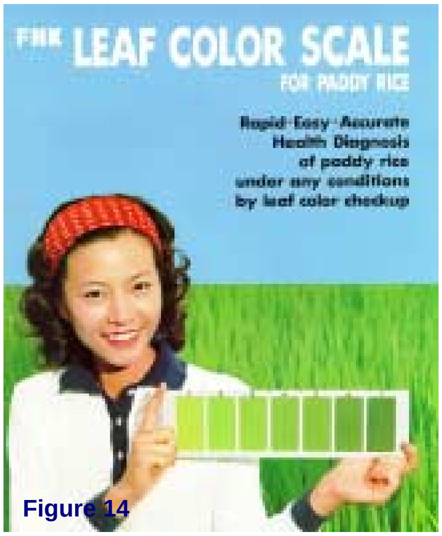


Figure 14

Unfertilised windows

One way to assess nitrogen needs throughout the seasons is to compare fertilised plants with unfertilised plants. If unfertilised plants are as green and healthy-looking as fertilised plants, the soil alone is providing enough nitrogen. When unfertilised plants are paler and smaller than fertilised plants, it means the soil does not contain much nitrogen in reserve, and larger side-dress applications of nitrogen to the crop may be in order.

How it works:
Reserve a small section of the field as the unfertilised window. Do not fertilise this window with nitrogen. At planting, fertilise with 40% of the normally recommended nitrogen fertiliser. When the regular top- or side-dressing date arrives, compare the window plants with the fertilised plants. If window plants show similar growth (in terms of size and colour) to that of the plants in the rest of the field, a subsequent application of only 10% of the originally recommended fertiliser is made. The application may vary from 10 to 60% depending on how the plants in the field compare with those in the control plot.

A window that is representative of the whole field can be made by shutting down the fertiliser spreader for a distance of about 25 m, creating a window 25 m long by the width of the spreader. Flag the window so that it can be identified with certainty during the growing season. The window may be difficult to keep completely free of nitrogen when fertiliser is broadcast rather than banded. Most broadcasting results in some overlap of passes, which would interfere with the window. In these cases, it may be impractical to use the unfertilised windows approach.

Figure 15

Indicator plants

Using the same unfertilised window approach, small plots located within the main crop can be used to grow “indicator” plants. These are generally fast-growing plants that have a deep root system and a strong ability to extract nutrients from the soil (e.g. oilseed radishes). The indicator plant is grown on a small section of the field where no nitrogen fertiliser is applied, and the growth characteristics of the indicator plant is used to estimate soil nitrogen content. Three weeks after the planting, the nitrogen content of the top 0-30 cm layer of soil can be estimated from symptoms of deficiency in the plant. Nitrogen content may be estimated for a layer of soil up to 60 cm deep after five weeks, and for a layer up to 90 cm deep after seven weeks.

With a little practice, this method can be used to obtain a fairly accurate indication of the amount of mineral nitrogen available in the soil. Another variation on this method involves fertilising some of the indicator plants, so that a comparison can be made using plants of the same crop, resulting in a better estimate of soil nitrogen.

3.2 Calculation-based methods

A producer or agronomist who wishes to refine the estimate of the required nitrogen can make calculations using different tools such as tables, expert systems or simulation models. Tables contain recommendations based on solid, agronomic research. Expert systems and simulation models are computer programs that estimate nitrogen fertiliser requirements using the parameters of the nitrogen balance. The difference between expert systems and simulation models lies primarily in the type of user. The former are available for producers and farm advisers, while the latter are intended for researchers.

3.2.1 Expert systems

Calculating a nitrogen balance based on figures in tables can be very tedious. A separate balance should be calculated for every field, and the more components that are included, the more time-consuming the process becomes. Moreover, in some places supermarket standards require that fertiliser management comply with established procedures, and producers are therefore obliged to maintain a field log. Québec farmers are required by regulation to keep a spreading register of application of all fertilising agents. Computer programs have been developed and are available on the market to help producers, produce efficient fertiliser recommendations and keep accurate records while reducing the amount of time devoted to fertiliser management. They frequently offer a user-friendly interface designed especially for agricultural producers and advisers. They generally produce recommendations for less nitrogen than producers would otherwise apply.[31] Many of the software packages that have been developed to estimate the nitrogen fertiliser requirements are cost-effective investments.

Three software packages for calculating nitrogen recommendations are described in this section: N-Expert II, Conseil-Champs and WELL-N.

N-Expert II

N-Expert II (Institute of Vegetable and Ornamental Crops, Groβbeeren, Germany) is a computer program that calculates field-specific fertiliser recommendations for vegetable crops. The calculations are based on simple plant growth models and soil models that require few input data. This, combined with a user-friendly interface, makes it accessible to both farmers and advisors. The nitrogen fertilisation recommendation is calculated in a balance sheet approach from six components: plant nitrogen uptake; required soil mineral nitrogen at harvest; nitrogen losses; soil mineral nitrogen at planting; nitrogen mineralisation from humus; and nitrogen mineralisation from crop residues. The user can enter field specific data, or accept standard values provided by a databank that includes all of the important vegetable crops. These data were derived from experiments conducted across Germany. The N-Expert software also provides recommendations for phosphorus, potassium, calcium and magnesium fertilisation. A demonstration version is available (in German) at the following Internet site: http://www.dainet.de/igz/n-expert/demo.htm .

Conseil-Champs, Agri-Champs

Agri-Gestion Laval is the creator and marketor of two fertiliser recommendation software packages. Conseil-Champs is a detailed package suitable for agronomists to use in advising their clients, while Agri-Champs is a simplified version of that is intended for use by the farmers themselves. These programmes take a balance sheet approach to recommending nitrogen fertiliser. Users enter the soil analysis, and analysis of substances such as limes, sludges and composts into the program. Other information, such as manure analysis, crop uptake and crop yield can be entered manually, or standard tabular values that are built into the program can be accepted. In calculating the nitrogen balance, the program accounts for mineralisation of soil organic matter, and the carry-over of nitrogen from crop residues and from manure applications made the previous fall. While it makes no allowance for leaching, it incorporates loss indices for manure nitrogen based on spreading equipment, manure type and incorporation practices. The program also recommends phosphorus and potassium fertiliser levels. Conseil-Champs is not particularly user-friendly and has some serious limitations (for example, it is very difficult to make recommendations for multiple crop cycles during one season). Conversion of Conseil-Champs from the DOS platform to Windows should take place in 2001.

WELL_N

WELL-N, a software package developed by Horticulture Research International in Wellesbourne, England, calculates the nitrogen fertiliser requirements of most crops grown in the United Kingdom.[14] The program uses meteorological, soil and crop data to calculate the nitrogen concentration of the soil and the quantity of nitrates susceptible to leaching for different types of fertiliser.

Two complementary models are integrated in the WELL-N software package; the first model uses data collected before the crop grows, and the second is a model that performs an automatic update when additional data are entered during the course of the growing season.[32] Although the software is available in its second version, its estimates of soil nitrate concentration remain too high, and further adjustments to the program are still required.

3.2.2 Simulation models

Simulation models can are used most commonly in research applications. These models are used to study the nitrogen interactions. By supplying these models with many data sets collected from experiments, researchers are able to determine which parameters are more or less important in the nitrogen interactions and which factors may be used to influence nitrogen balances.

Models that most effectively predict the nitrogen requirements of vegetables are those that incorporate data on local meteorological conditions.[33] The following parameters are often used in simulation models to calculate the movement of nitrates in the soil and leaching:

- Concentration of soil mineral nitrogen
- Distribution of soil mineral nitrogen in the soil profile
- Organic matter (readily decomposable, slowly decomposable)
- Field capacity at different depths
- Evaporation (precipitation, wind, light conditions, relative humidity of the air)
- Daily temperature (air, soil)
- Mineralisation rate
- Plant uptake of nitrogen
- Plant uptake of water

N-Able is an example of a simulation model. It can be found at the following Internet site: http://www.qpais.co.uk/nable/nitrogen.htm .

3.3 Methods based on soil and plant analyses

Nitrogen fertiliser needs can be determined from soil and plant analyses. N_{min} and KNS (Kulturebegleitende Nmin Sollwerte) are two methods for developing fertiliser recommendations based on measurements of soil mineral nitrogen. Sap tests, chlorophyll readings and total nitrogen analysis are used in methods that determine nitrogen fertiliser requirement on the basis plant tissue nitrogen measurement.

Scientists have been studying the use of sap and soil tests in managing nitrogen fertilisation of vegetable crops. While everybody seems to agree that adjusting fertiliser recommendations according to soil mineral nitrogen test results in spring is a good practice, the best method for monitoring crop nitrogen status during the growing season is open to more debate. Researchers in California have found that in irrigated lettuce production, presidedress soil nitrate testing is far superior to presidedress sap nitrate testing.[34] Yet in Minnesota, potato producers in areas where the soil is conducive to leaching (sandy soil) reduced their fertiliser costs and made reduced leaching losses fertilising according to sap tests.[35] In Québec, study has shown that sap testing holds promise as a tool for deciding the rate of nitrogen fertiliser to apply to broccoli at side-dressing.[36] It may very well be that certain crops are well monitored using sap tests, whereas others do not exhibit as strong a correlation between sap nitrate and nitrogen supply, and are therefore better managed using soil nitrate testing.

3.3.1 Soil

Testing soil nitrogen is only useful if the sample tested is representative of the field to be fertilised. This entails following a defined soil sampling method.[21] Because of the varied nature of soil and particularly of its nitrogen level, it is essential that numerous sub-samples be collected; these are grouped by depth and mixed carefully in pails from which samples representing the whole field (at the given depth) are taken. The depth at which soil samples are collected must be consistent with the depth of the roots of the crop: 0-30 cm, 0-60 cm or 0-90 cm (Table 8). Plants exploit mineral nitrogen from different soil depths, depending on root capacity.

Table 8: Rooting depth of some vegetable crops

Root zone		
0-30 cm	**0-60 cm**	**0-90 cm**
Kohlrabi	Beans	Asparagus
Lettuce, leaf	Broccoli	Brussels sprouts
Lettuce, iceberg	Cabbage, early	Cabbage, late
Peas	Cauliflower	Cereals
Radish	Celery	Corn
Spinach	Endive	Rape
	Leek	
	Potato	

Scharpf, 1991

Studies have shown that quality of the results obtained from soil analysis is directly proportional to the care taken during sampling, sample preservation and analysis. Once a sample has been collected, it must be chilled quickly to prevent any changes in nitrate content while it is awaiting analysis.[37] In order to be able to confidently compare the results of different samplings, it is also important that one method for determining soil mineral nitrogen concentration in the samples be used consistently.

3.3.2 Plants

Like soil nitrate concentrations, nitrate concentrations in plants are far from homogeneous. Therefore numerous sub-samples, collected in a representative manner, must be used to make one sample. One sample should comprise tissue from about twenty plants collected throughout the field. Because nitrogen is mobile in plants, and travels from old tissues to newer ones, the youngest newly expanded leaf is usually selected from each plant. Various measurements of nitrogen can be made from plant samples. Some tests are destructive; sap nitrate tests and total nitrogen analysis require the leaves to be removed from the plants. The chlorophyll meter, on the other hand, can be used to measure tissue nitrogen of intact, growing leaves.

Sap tests

Sap nitrate tests can be used to monitor the nitrogen status of plants. Once absorbed by the roots, nitrogen is transported to the leaves where it is transformed and incorporated into the living material. Although part of this transformation may take place in the roots rather than the leaves, nitrate concentration in the aerial part of the plant provides a good indication of whether the plant is receiving an adequate supply of nitrogen. The nitrate concentration is therefore measured in a representative part of the plant in order to identify any deficiencies. The sap from the leaf petioles tends to give the best indication of plant nitrogen status because it is more sensitive to fluctuations in nitrogen supply than the leaf blade extract is.

Nitrate test strips and reflectometer

Nitrate can be measured in sap using Merkoquant test strips and a Nitrachek reflectometer (full methodology appears in Appendix II). Merckoquant test strips are specially treated to react in the presence of NO_3^- by producing a colour, the intensity of which varies directly with the concentration. This test appears to be universally popular because it combines economy, precision and ease of use. The quick tests are very highly correlated to conventional laboratory analysis[37], so they are very good alternative. The colour of the strip can be evaluated by visual comparison with a colour chart or by reflectometers, devices that have been developed to eliminate human subjectivity. The most commonly used nitrate quick test is the Nitrachek reflectometer, distributed in Québec by the company Geneq. The nitrate test strips and reflectometer can also be used to measure nitrate in soil solution.

Figure 16

Ion-specific electrodes

Another quick test of sap nitrate uses an electrode with a membrane porous to a specific ion: in this case, the nitrate ion. Two such devices are currently available on the market: *Horiba/Cardy meters* (Horiba Co., Japan) distributed in North America by Spectrum Technologies (Plainfield, IL), and a similar device produced by the Hach Co. (Loveland, CO). There is a high correlation between results obtained using ion-specific electrodes and those obtained in a laboratory.[38,39,40] It should be noted that the ion-specific electrode can also be used to determine the nitrate concentration in soil solution.

Chlorophyll measurements

The SPAD meter by the Minolta Corporation (Ramsey, NJ) reacts instantly to the chlorophyll in the leaves. The meter detects differences in chlorophyll content by measuring the amount of light transmitted through leaves and interpreting the data with respect to the properties of chlorophyll and the electromagnetic spectrum. This information can be used to assess the nitrogen nutritional status of the plant.

The device is accurate, sensitive, simple to use and requires no chemicals, preparation or destructive sampling. While chlorophyll content is usually highly correlated to nitrogen content, the chlorophyll level can also vary by the cultivar, the environmental conditions, the growth stage of the plant,[40] disease, pests and cold temperatures.[41] For this reason, the SPAD meter cannot be used by the farmer to the exclusion of other crop and meteorological monitoring. Some of the effects of these other factors on the chlorophyll level may not affect the usefulness of the readings in fertilisation planning if readings from plants in the field to be fertilised are compared with those from an over-fertilised test strip in the same field, where the same factors are at play. The SPAD meter is often thought of as an investment because of its relatively high cost.

Figure 17

N Sensor and precision agriculture

The N-Sensor is a control device, developed in Germany by the agricultural research subsidiary Hydro Agri International, for variable-rate application of nitrogen. The N-Sensor operates in “real time,” detecting the crop’s nitrogen requirements on the basis of reflectance from the plant cover, and immediately translating the measurements obtained into fertiliser applications. In practice, the system is integrated into the tractor and fertiliser spreader, and takes measurements during the application of sidedress applications. As the device detects the nitrogen needs, the spreader is calibrated to the appropriate rate.

In Europe, where the N-Sensor was developed for small grain crops, it has proven to be an effective tool; crops produced using the technology had greater, more uniform yields of grain, and higher protein concentration than those produced without it. Lodging was also reduced. In addition, nitrogen use was better managed resulting in a lowered risk of pollution.

In Québec, the N-Sensor technology would be particularly useful to farmers when top-dressing nitrogen in seed corn and potatoes. Tests are underway to adapt the technology to these crops in Québec.

Total nitrogen analysis

This method involves determining the total amount of all forms of nitrogen present in plant tissues. In this method, the tissues are dried, finely ground, digested in an acid solution and then quantitatively analysed. As in the case of soil sampling, great care must be taken in tissue sampling. Total nitrogen in the plant is related to both the amount of nitrogen in the sap, and the amount of nitrogen that has already been incorporated into organic compounds, such as chlorophyll, in the plant tissues. Total nitrogen analysis is limited in use when adjusting nitrogen fertilisation mid-season because it may take days or even weeks to receive the results from the laboratory. It is not a test that farmers can perform themselves.

3.3.3 Using soil and sap nitrate measurements

A common cause of over-fertilisation is disregard for the plant available nitrogen in the soil. Reducing a fertiliser recommendation by the amount of nitrogen supplied by the soil is a key to efficient fertilising. It is important to note that monitoring sap nitrate provides essentially the same information as soil nitrate testing. Sap nitrate can be correlated to nitrogen supply from the soil, and therefore, just as these methods describe reducing fertiliser applications according to soil nitrate, fertiliser recommendations can also be adjusted using similar principles according to sap nitrate analysis.

N_{min} method

The N_{min} (for mineral nitrogen) method[42] of developing nitrogen fertiliser recommendations uses an actual measurement of soil nitrogen in the calculations. The concentration of mineral nitrogen is determined from a soil sample collected early in the field season, before seeding or transplanting takes place. This concentration is subtracted from a target nitrogen fertilisation value to give the final fertiliser recommendation. Provided the soil sampling and nitrate analysis are carried out with care and precision, and that the target nitrogen fertiliser values are based on local experimentation, the N_{min} method results in precise recommendations suited to each field. Under these conditions, the N_{min} method is more exact than using average-value tables or approximations based on observations. The three main principles of the N_{min} method are summarised below.

Principles

1- Soil sampling depth must correspond to the root depth of the crop.

2- Nitrogen in the soil must be quantified because it makes an effective contribution to the crop. The more nitrogen the soil contains, the less must be applied (Figure 18).

3- For each crop, there is a specific target level of nitrogen that must be available for maximum growth and yield to occur. The target value is determined experimentally, and is the sum of nitrogen already in the soil and nitrogen supplied by the application of fertilisers. In the case of lettuce (Table 9) the target value was determined to be 130 to 150 kg N/ha.

Figure 18

Effect of different topdress nitrogen fertiliser applications on the yield of iceberg lettuce grown using five levels of nitrogen at planting

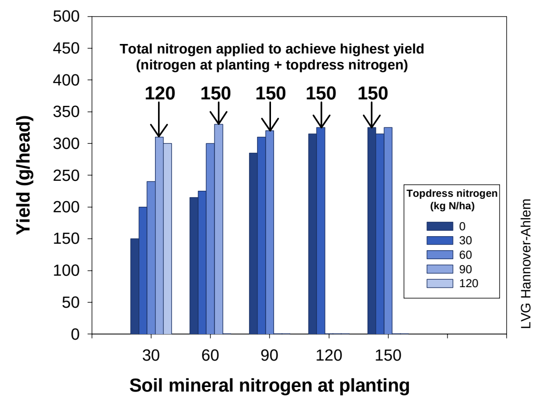


Table 9: Nmin method fertilisation target values for some vegetable crops

Nmin target value category	Target values	Crop
Very low	80-100	Asparagus Carrot Chicory Peas
Low	130-150	Beans, dwarf Beans, pole Lettuce, leaf Lettuce, iceberg Radicchio
Average	160-200	Endive Kohlrabi Onion Radish Spinach
High	220-250	Beets Brussels sprouts Cabbage, early Cabbage, Chinese Celery Leek Radish, Japanese Rhubarb
Very high	300-350	Broccoli Cabbage, late Cabbage, processing Cauliflower

Scharpf, 1991

The N_{min} method improves fertiliser management by better matching nitrogen supply to crop needs, so the method is highly recommended in areas of intensive vegetable farming (such as in the Palatinate area of Germany, or the Montérégie region of Québec), particularly for farms located near drinking water sources, where the danger of polluting is high. Unfortunately, sampling and analysis are not always practicable. Farms may be located at a considerable distance from a laboratory, and farmers often manage multiple crops, each requiring the additional labour of sampling for separate analyses. However, a solution is on the way! The development of nitrate quick tests may allow farmers to use the N_{min} method more easily. A complete method for a soil nitrate quick test is included in Appendix I.

Using the "target value" approach

The N_{min} target value represents the total amount of nitrogen that must be supplied to the crop for optimal yield. If the soil mineral nitrogen measured before cropping were equal to zero, the fertiliser recommendation would equal the target value. But in reality, unless exceptionally heavy precipitation has occurred, the soil contains a significant amount of nitrate, and therefore the recommendation must be less than the target value. Exceeding the target value inevitably leads to over-fertilisation and an increased risk of environmental pollution.

Target values integrate the capacity of the soil to release nitrogen from the mineralisation of humus throughout the growing season. Environmental effects, soil characteristics and cropping practices that affect this mineralisation vary considerably from region to region; therefore the N_{min} target values should be based on local experimentation.

Modifying the "target value" approach

While the N_{min} method accounts for mineralisation from humus throughout the season, it does not account for the incorporation of fresh organic matter, which releases an additional amount of nitrogen. This is of little importance if a crop is planted into a field where no fresh material is incorporated just before or at planting. However, if massive amounts of readily decomposable organic matter are applied at the time of planting or transplanting, a significant amount of nitrogen will be released and should be taken into consideration when making fertiliser recommendations. This can be accomplished by modifying the N_{min} method. The KNS method does this.

KNS method

While the N_{min} method is used when deciding how much nitrogen to apply, the KNS method[43] uses similar principles when deciding how much of the recommended nitrogen to apply at planting and as top- or side-dress applications during the growing season. Instead of just one target value, KNS uses target values that differ throughout the season. Any number of supplementary nitrogen applications can be made, based on date-specific target values and soil mineral nitrogen tests prior to top or sidedressing.

The KNS method offers the following advantages: sampling can be flexible (in terms of dates); data collection can be spread throughout the season, which is an advantage for the laboratories, because they often have too much work in the period preceding planting or transplanting; information can be obtained on mineralisation (speed, quantity). However, whether or not the mineral nitrogen in the fresh organic matter is detectable in the analyses depends the speed at which the nitrogen is released.

4 Nitrogen balance

The concept of a nitrogen balance is an important one. It considers various interactions of the nitrogen cycle as inputs or outputs to the cropping system. The difference between inputs and outputs shows how much nitrogen should be applied for efficient fertilisation. This balance approach is the basis for many of the computer software programs designed for making nitrogen recommendations, but it can also be easily computed by hand, using values from tables. Because it takes into account the important inputs and outputs, using a nitrogen balance to calculate nitrogen fertilisation recommendations is perhaps the best way of efficiently fertilising vegetable crops. It is designed specifically to apply in fertiliser only what is needed to meet the crop objectives for yield and quality. Using the nitrogen balance when fertilising

4.1 Using the nitrogen balance when fertilising

It is very important to remember that the inputs and outputs of the nitrogen balance are not all equal in terms of the quantity of mineral nitrogen they add or remove from the soil (Figure 19). The specific contribution of each component of the nitrogen balance depends on its role and its relative importance. Certain inputs must always be considered: residual nitrogen (soil nitrogen available in spring) and nitrogen from mineralisation. The amount of nitrogen introduced by irrigation water must sometimes be taken into account, while it is generally unnecessary to include nitrogen from precipitation in the calculation (Table 10).

In the same way, certain outputs are vital in the calculation of nitrogen balance: the amount of nitrogen absorbed by the crop, the safety margin (an output because it remains after harvest) and the nitrogen that is not available due to immobilisation. The quantity of nitrate leached must sometimes be calculated, but is not essential if precipitation is negligible. Denitrification need not be calculated. Vegetable fields are usually well drained, and denitrification is often roughly equivalent to the input by precipitation (Table 10).

4.1.1 Where do the values come from?

Different methods have been developed to estimate or measure the values for calculating the nitrogen balance. Measurements made using sap or soil tests, when practical, are often better than estimates, for a certain amount of error is introduced by estimation that may be avoided by measurement. The following examples of nitrogen balance are calculated using estimates of inputs and outputs taken from tables of empirically derived, and in some cases, using direct measurements that can be made. Since growing conditions vary greatly by region, the best tables to use are those that have been developed locally.

Soil mineral nitrogen in spring or between two crops

Nitrogen levels in the soil may be estimated at two times: in the spring and between two crop cycles (in regions where producers plant more than one

Figure 19

Relative importance of the main inputs and outputs in the nitrogen balance

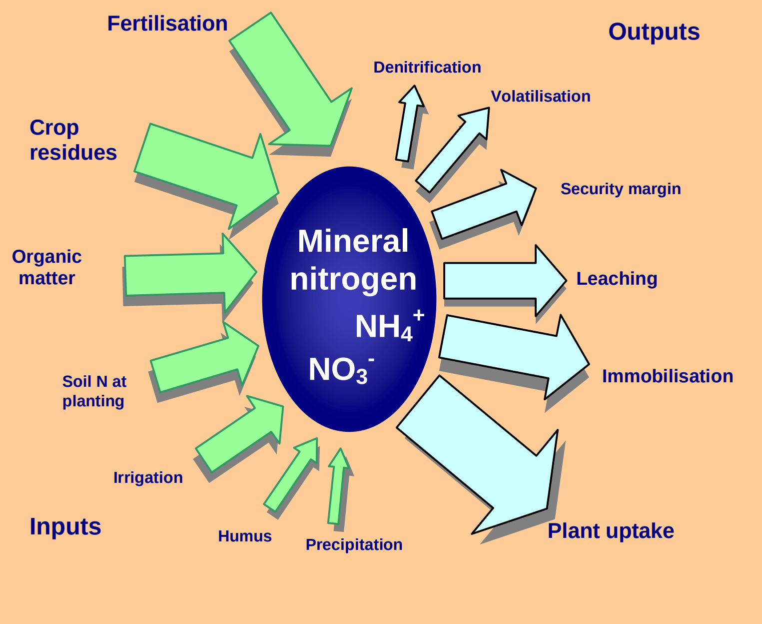


Table 10: Relative importance of nitrogen inputs and outputs in nitrogen balance calculation

Priority	Inputs	Outputs
Always considered	• Crop residues • Mineralisation of soil organic matter • Soil mineral nitrogen in spring	• Crop uptake • Safety margin • Immobilisation
Occasionally considered	• Irrigation	• Leaching
Rarely considered	• Precipitation	• Denitrification

Table 11: Example of a table for estimating soil mineral nitrogen in spring in the 0- to 60-cm soil layer. This table is adapted to mild winter conditions and not for use in Québec

	Sand		Loamy sand		Loam	
Quantity of previous-crop residue N	Small[1]	Large[2]	Small	Large	Small	Large
Precipitation November to March	Estimated Soil Mineral Nitrogen in Spring (kg N/ha)					
100 mm	30	50	80	150	130	200
200 mm	20	30	30	100	80	150
300 mm	20	20	20	50	30	10

[1]e.g.; lettuce—releases about 30 kg N/ha

[2]e.g.; cabbage—releases about 100 kg N/ha

Adapted from Scharpf, 1991

crop cycle per year). Different factors are taken into consideration in each case.

When an estimate is made in the spring, the following factors must be considered: the mineral nitrogen concentration of the soil the previous fall, the mineralisation and nitrification potential of the crop residue over the winter season, and nitrate denitrification and leaching during the thaw (Figure 4).

Table 11 is an example of a table of standard values for estimating the amount of nitrogen present in spring in Germany. For example, a value of 20 kg/ha constitutes the estimate of residual nitrogen in a sandy soil (easily leached) that has received average to heavy winter precipitation. Conversely, a nitrogen residue of 200 kg/ha is estimated for a loam to which cabbage crop residue has been added that has received light winter precipitation. Because so many factors are involved in nitrogen flux during winter, and the interactions are based to a great degree on climatic factors, a great deal of research goes into creating a table of standard values for estimating soil mineral nitrogen in spring. Such a table is not available for vegetable-growing regions that experience a cold, harsh winter of five months with more than 350 mm of snowfall, as is the case in Québec. Perhaps such a table will become available in the future. The alternative is to use a nitrate quick test in spring to measure soil mineral nitrogen. This can be included in the nitrogen balance calculation as shown in Table 13.

Two other inputs must be considered if the estimate is made between two crop cycles during the same season: the quantity of mineral nitrogen available in the soil after the first crop--the safety margin (Table 4) and the readily mineralisable crop residue left behind by the first crop--the crop residues (Table 3). These can be included in the nitrogen balance calculation as shown in (Table 14). With the exception of heavy or steady rains on light soils or in the case of shallow-rooted crops, the effect of precipitation on residual nitrogen during the summer is negligible.

Mineralisation of humus

The amount of nitrogen that will become available to the crop during the gowing season is determined by a very simple calculation. Mineralisation of humus is approximately 5 kg N/week. Therefore, multiply 5 kg N/week by the duration of the growing season in weeks.

Crop residues

When inputs of residues from previous crop or mineral fertilisers are high, mineralisation tends to exceed immobilisation. In such cases, mineralisation and immobilisation do not cancel each other, and must be considered separately.

Table 3 provides values that may be used in Europe and in Québec. These values were calculated by multiplying the number of tonnes of yield by 3 kg N/tonne, which is the average amount of nitrogen that the residues contain. However, because only 70% of the nitrogen is likely to be mineralised during the season, the values found in Table 3 should be multiplied by 0.70 to render the amount of mineralisable nitrogen. In Québec, a further calculation should be made to account for the loss of nitrogen from crop residues throughout the winter and spring. Realistically, only about 25% of the nitrogen in crop residues remains in the cropping zone of the soil by the end of spring. Therefore, multiply by 0.25 to arrive at the final value to include in the nitrogen balance.

The nitrogen in compost is primarily present in organic form and is not available to the crop in the short term. Only the mineral nitrogen present in the compost should be included in the balance. This quantity of nitrogen must be determined by lab analysis, since it is too difficult to estimate.

The mineral nitrogen content of solid and liquid manures can be measured through lab analysis, or taken from locally available tables.

Uptake by the plant

The amount of mineral nitrogen taken up by the plant depends on the crop and the yield. Table 4 contains data on the nitrogen requirements of various crops and their average yields. If the expected yield lies outside the range indicated, a ratio calculation can be made to adjust the requirements accordingly.

Safety margin

Table 5 presents a number of safety margins, which vary considerably from crop to crop.

Immobilised or unavailable nitrogen

Approximately 15 to 20% of the mineral nitrogen, be it incorporated or already present in the top layer of the soil, is immobilised by microorganisms or is unavailable to plants through processes such as ammonium fixation.

Irrigation water

The amount of nitrogen introduced by irrigation water need not be included in the nitrogen balance unless it exceeds the threshold of 30-40 kg of nitrogen per season.

> **Conversion of nitrate to nitrogen equivalent…**
>
> An input of X mg/L of nitrate can be converted to a nitrogen input (kg/ha) by dividing by 4.43. For example, 100 mm of irrigation at a nitrate concentration of 100 mg/L would introduce 22.5 kg of nitrogen per hectare.

Leaching

In Québec, leaching of nitrate occurs mainly in early spring and in fall. The nitrogen balance accounts for the processes that occur throughout the growing season, during which time, leaching is negligible.

Precipitation and denitrification

Nitrate input from precipitation is equivalent to nitrate lost through denitrification. These two processes cancel each other in most cases and need not be measured or factored into nitrogen balance calculations.

4.1.2 Sample calculation

Tables 12, 13, 14 show how to create a nitrogen balance by subtracting outputs from inputs. If the result of subtracting outputs from inputs is positive, fertilisation is not necessary since the soil will supply sufficient nitrogen to meet the plants' needs. However, if the result is negative, nitrogen fertilisation is needed in order to satisfy the plants' requirements. The amount of fertiliser required corresponds to the magnitude of the negative value. The negative balances in Tables 12, 13 and 14 indicate that fertiliser is required to compensate for nitrogen losses and meet the needs of the crops.

Fertiliser management is handled much the same in the case of the second crop of a season (in areas where applicable). The safety margin from the first crop will still be available in the soil for the second crop. While this may be accommodated by entering the amount of the safety margin of the first crop as an input for the second crop, the better alternative is to use a soil nitrate test to measure the soil mineral nitrogen instead. Table 14 shows the fertiliser needs of a crop of carrot that follows a crop of lettuce.

Using a nitrogen balance to determine the amount of fertiliser to apply is great improvement in fertiliser management compared to following general fertilisation guidebooks or relying on guesses, rules of thumb and imprecise observations. Using measurements for values of soil nitrate, nitrogen concentration of crop residues and other values can render the nitrogen even more accurate than using tabular values in the calculation.

Table 12: Example of two nitrogen balances. In both cases, the current crop is cauliflower. The first balance shows the calculation if the previous year's crop was carrot. The second balance shows the calculation if the previous year's crop was lettuce

Present Crop **Cauliflower**	Text reference	Preceding crop **Carrot**	Preceding crop **Lettuce**
Growing season (weeks)		24	10
Inputs	2.1		
Soil mineral nitrogen in spring estimated from a table (kg N/ha)	2.1.1 4.1.1 Table 11	20*	20*
Crop residues (kg N/ha*0.70*0.25)	2.1.2 4.1.1 Table 3	10	5
Mineralisation (5 kg N/ha per week*weeks)	2.1.2 4.1.1	50	50
Total inputs		80	75
Outputs	2.2		
Plant uptake (kg N/ha)	2.2.1 4.1.1 Table 4	260	260
Safety margin (kg N/ha)	2.2.1 4.1.1 Table 5	75	75
Immobilisation ((uptake+safety margin)*0.15) (kg N/ha)	2.2.2 4.1.1	50	50
Total outputs		285	285
Nitrogen Balance (fertiliser needs) (inputs – outputs)	4.1	-205	-210

*small quantity, 30 kg N/ha, loamy sand, 300 mm precipitation

Table 13: Example of a nitrogen balance calculation using a value of soil mineral nitrogen in spring measured using a nitrate quick test

Present Crop **Carrot**	Text reference	Preceding crop Cauliflower
Growing season (weeks)		24
Inputs	2.1	
Soil mineral N in spring from nitrate quick test (kg/ha)	3.3.2 Annex I	35
Crop residues (kg N/ha*0.70*0.25)	2.1.2 4.1.1 Table 3	18
Mineralisation (5 kg N/ha per week*weeks)	2.1.2 4.1.1	120
Total inputs		173
Outputs	2.2	
Plant uptake (kg N/ha)	2.2.1 4.1.1 Table 4	160
Safety margin (kg N/ha)	2.2.1 4.1.1 Table 5	45
Immobilisation ((uptake+safety margin)*0.15) (kg N/ha)	2.2.2 4.1.1	30
Total outputs		235
Nitrogen Balance (fertiliser needs) (inputs-outputs)	4.1	-62

Table 14: Example of a nitrogen balance calculation for the second crop in a single season

Present Crop **Carrot**	Text reference	Preceding crop **Lettuce**
Growing season (weeks)		24
Inputs	2.1	
Soil mineral N between crops measured using nitrate quick test (kg N/ha)	3.3.2 Annex I	15
Crop residues (kg N/ha*0.70)	2.1.2 Table 2	5
Mineralisation (5 kg N/ha per week*weeks)	2.1.2	120
Total inputs		140
Outputs	2.2	
Plant uptake (kg N/ha)	2.2.1 Table 2	160
Safety margin (kg N/ha)	2.2.1 Table 3	25
Immobilisation ((uptake+safety margin)*0.15) (kg N/ha)	2.2.2	28
Total outputs		213
Nitrogen Balance (fertiliser needs) (inputs – outputs)	4.1	-73

5 Prevention of nitrogen leaching

Leaching (Section 2.2.2, leaching) is movement of substances with water down through and out of the soil, into the groundwater. Nitrate is an easily leached substance that is widely used as fertiliser, and which if improperly managed can cause water pollution. In Canada, nitrate-nitrogen levels in excess of 10 ppm in drinking water are considered harmful to human health.[44] Nitrates can be fatal to nursing infants, particularly those between the ages of three and six months.[45] Once ingested, nitrates can converted to toxic nitrites in the infants' digestive tracts, causing an oxygen deficiency called **methemoglobinemia**. In the majority of the cases attributed to contaminated drinking water, the nitrate nitrogen content of the water was greater than 40 mg of nitrate-nitrogen per litre, or four times the maximum acceptable concentration in Canada.[46] Nitrates affect ecosystems as well as human health. The presence of nitrates and phosphates in streams leads to eutrophication,[44] which transforms lakes and ponds into bogs and ultimately leads to the complete drying-up of the body of water.

Methemoglobinemia (blue baby syndrome)

Methemoglobinemia (blue baby syndrome) can be fatal, especially in infants and children. Most documented cases have been caused by excessive nitrate levels in drinking water. However, it is also interesting to note that the incidence of methemoglobinemia declined sharply during the early 1950's, to such an extent that many of the health reporting agencies in the United States, including the National Institute of Health and the National Center for Disease Control, stopped collecting statistics about it because it was so rare.[28] While methemoglobinemia declined, fertiliser use sharply increased.

However, over-fertilisation of crops is a significant source of nitrate in ground water. If the incidence of methemoglobinemia is to continue to be low, all of the agricultural sectors must play a role in preventing nitrate pollution.

Nitrate pollution in Québec

Nitrate levels in natural watercourses are often less than 0.2 mg N/L, but in some of Québec's rivers, the nitrate concentrations are much higher. Watercourses that run through farmland have higher concentrations than those running through forest, and this has prompted some study of the influence of agriculture on water quality. A study of 22 agricultural watersheds in Québec revealed that the main factors influencing nitrate flux were the density of human population, the intensity of animal production and wide-row crops, such as corn, potatoes and many vegetable crops.[53] Often, vegetable production is overlooked as a cause of nitrate production because vegetable crops represent a much smaller land area than corn, which is often cited as of a heavily fertilised crop that leads to soil erosion and leaching. But a study of the Norton Stream, in the prime vegetable growing of Montérégie, compared the inputs and outputs of corn and vegetable cropping systems and came up with some eye-opening results.[54] Vegetable cropping systems left more than double the amount of nitrate in the soil after harvest as cash cropping systems did (Table 15). While nitrate levels in Québec's watercourses are still lower in general than the Canadian standard of 10 mg N/L, it is clear that measures must be taken to safeguard the quality of water, and that improving the efficiency of fertiliser use in cropping systems is one place to begin.

The regulation on the reduction of pollution from agricultural sources[19] sets forth some limits on nitrogen use. Manure-nitrogen must not exceed the limits for each crop set in the regulation, and the quantity of fertiliser spread must be based on the plant requirements and take into consideration nitrogen from mineralisation of soil organic matter, and nitrogen from mineralisation from crop residues.

Table 15: Comparison of the global cash crop nitrogen balance to the global vegetable crop nitrogen balance in the watershed of Corbin Stream in Québec

	Cash crops	Vegetable crops
Nitrogen inputs	183	155
Nitrogen outputs	132	35
Balance	52	120

Adapted from Demarais and Breune, 1998

Some governments (Switzerland, Finland, Austria and Belgium) limit the maximum amount of nitrogen allowable in one application, or the total nitrogen supply to a crop in an effort to reduce nitrate pollution of water (Québec). When nitrogen is lost through leaching, it represents not only an environmental concern to farmers, but also a money sink. Regulations that simply limit nitrogen applications may not encourage farmers to manipulate other aspects of fertiliser management to decrease leaching. Understanding the many factors that influence leaching can show farmers many ways to reduce leaching, saving money while preventing pollution.

5.1 Improved fertiliser management

Controlling nitrogen fertilisation is the best way of reducing nitrate leaching. The farmer has the power to decide the quantity of fertiliser, when and how to apply it. All three factors will influence the risk of nitrate leaching in a given field.

5.1.1 Quantity of fertiliser

Farmers often use high levels of nitrogen to achieve high yields. However, increasing nitrogen infinitely will not lead to infinitely higher yields. Nitrogen use by plants is governed by the law of diminishing returns; as yields increase, the net gain for the farmer decreases. Every additional kilogram of nitrogen applied costs the same; but the yield increase becomes smaller and smaller. At a certain point, the cost of an additional kilogram of fertiliser does not bring enough profit to warrant its use.

In addition, crop yield can be limited by factors unrelated to nitrogen fertiliser availability, such as heat units or growing degree-days, soil moisture and the genetic characteristics of the cultivar. Another nutrient may be limiting, preventing the plant from growing and using nitrogen fertiliser. Increasing fertiliser application above optimal levels will not override the other limiting factors.

One way to know if a field has been over-fertilised is to test the soil nitrogen content after harvest. The safety margin should still be present in the soil, corresponding to 30 to 90 kg N/ha, depending on the crop grown (Table 5). When over 90 kg N/ha is present, the field has been over-fertilised.

5.1.2 Fertiliser handling (where, when, what kind)

Split applications

To prevent leaching, several fertiliser applications (split applications) are preferable to one.[47] If all fertilisers are applied at once, and heavy precipitation ensues, a significant quantity of nitrate will be leached. An equally important benefit to using split-applications is that yields may be improved because the supply of nitrogen is better timed to the development of the crop.[48]

Fertigation, a technique that involves adding fertiliser directly to irrigation water, is a flexible and efficient way of delivering of split-applications of fertiliser. Drip tapes that carry the fertigation solution are placed very near to the base of the plants. Watering is usually done weekly, but may sometimes be done on a daily basis. Caution must be exercised when using fertigation because the risk of leaching increases with water volume. Fertigation is also a promising way of reducing variability in yield response to nitrogen caused by varying soil texture.[49] Tests of tomato crops revealed increased yield where fertigation treatments were applied compared with non-fertigated plants.[49]

Slow-release fertilisation

A slow-release fertiliser is one that releases its nutrients, particularly nitrogen, at a predetermined rate after application. Slow-release fertilisers serve the same purpose as split-application; they provide nitrogen as the plant requires it.

One of the benefits of using this slow-release fertiliser is that it saves time. All the fertiliser can be applied at once, at the beginning of the season. The risk of loss due to leaching is reduced, and the producer is not obliged to return to the field to fertilise.

Slow-release fertilisers also have a number of very real disadvantages: they may require special equipment; they are more costly than conventional fertilisers; nitrogen release may not coincide with crop requirements; nitrogen contribution through mineralisation is not factored into the initial amount of fertiliser applied; and soil analysis becomes more difficult to interpret.

The sellers of this type of fertiliser are well informed about them and are able to provide the specific characteristics of each (coated, polymerized, concentrated, with nitrification inhibitors, relatively water soluble and water insoluble).

Placement of fertilisers

To prevent leaching, fertilisers must be placed near the plants, particularly in the case of a crop, such as pumpkin, that is grown in rows spaced relatively far apart. Banding is a method of applying fertiliser in a concentrated vein near the seed or young plants' roots, where it may be efficiently taken up. In a study on onion, banding 14 kg/ha of nitrogen resulted in the same yield as broadcasting 80 kg N/ha.[50]

Foliar application

A sprayer can be used to apply fertilisers to the leaves of plants. This is a common method of application for secondary and micronutrients, but can be used to supply plants with nitrogen. Leaves can absorb minerals, but do so less effectively than roots do. It is not possible to supply the crop's entire nitrogen requirement through foliar application.

Certain precautions must be taken when using foliar fertilisers. Avoid applying the fertiliser when the sun is shining, when it is very dry or windy. Under these conditions, evaporation is very rapid, and the risk of burning the leaf is increased. Follow the manufacturer's recommendations regarding maximum dilution.

Perhaps the best use of foliar application of fertiliser is to correct a nutrient deficiency. In some stages of plant growth, adequate nutrition is essential. Foliar-applied fertiliser is absorbed very quickly and may work to correct a deficiency more quickly than soil-applied fertiliser.

5.2 Crop growth

Healthy crop growth is one of the best preventions against nitrate leaching. Healthy crops grow well, absorbing nitrogen quickly from the soil.

5.3 Green manures (or trap crops)

Green manure crops are grown specifically to be turned under to add organic matter to the soil. Non-vegetable green manures can help reduce nitrate leaching in two ways: they absorb nitrate and reduce the amount of drainage by taking up water.[27] Some crops, such as oilseed radishes, mustard, and barley, have long root systems that are capable of removing nitrate from deep in the soil profile. Wheat or crimson clover (*Trifolium incarnatum*) can also be planted as green manures to extract nitrate from the soil. Wheat takes up more soil nitrate than clover does.[51] Soy is another crop that is effective at taking up soil nitrate.[52]

A green manure can be planted immediately after harvesting a vegetable crop in July or August. The green manure grows and takes up any excess mineral nitrogen and the nitrogen that becomes available quickly from the fresh vegetable crop residues. This nitrogen is prevented from leaching with fall precipitation. Timing the incorporation of the green manure is the key to efficient nitrogen use. It should be incorporated as late as possible in the season, so that the organic matter will freeze before mineralisation can occur. When the ground thaws in spring, mineralisation will occur as the temperature increases and oxygen becomes available (i.e. after flooding has subsided). This coincides with the beginning of cropping season, making the nitrogen available at just the right time!

Planting a green manure while the vegetable crop was still growing proved unsuccessful when tested in Germany. However, if time is short, the green manure can be seeded directly into the residue of the vegetable crop. This method has been used in broccoli, red cabbage, late spinach, Brussels sprouts and cauliflower production. The disadvantage of leaving a residue in place is that such a practice allows disease and weeds to establish themselves.

5.4 Organic fertiliser

Incorporation of organic fertilisers such as manure or compost increases the amount of leachable nitrogen in the soil because the mineral nitrogen fraction is directly open to leaching. In time, organic nitrogen will also be mineralised and subject to leaching. Because of these effects, it is preferable to incorporate manures and composts very late in the season so that freezing occurs soon after, or in the spring and early summer, when the mineral nitrogen can be used immediately for crop growth, and temperatures favour mineralisation. Crop plants can use the mineralised nitrogen later in the production cycle.

5.5 Other fertiliser sources

In some countries, calcium cyanamide ($CaCN_2$, 22-0-0) is approved for use as a herbicide. It also acts as a fertiliser, and its nitrogen input (between 20 and 22%) must be included in the nitrogen balance.

5.6 Crop residues

5.6.1 Methods of incorporation

Crop residues are organic matter, and the same concerns that apply to other organic matter amendments also apply to crop residues. There are various methods of incorporating crop residues, but what is most important is that they be worked in as late as possible: before winter or in spring. In this way, the risk of leaching is reduced because low temperatures slow nitrogen release.

Care should be taken if crop residues are to be ploughed into the soil. Ploughing operations that result in complete inversion of the soil result in very slow rates of mineralisation of crop residues, because oxygen is often scarce where the residues are placed. Operations that cause the ridges to overlap at a sharp angle are more suitable for favouring mineralisation. The ridges trap moisture, and also allow adequate oxygen to penetrate the furrows. Allowing residues to mineralise efficiently is important in planning fertilisation, but in reality, ploughing the soil does not really affect leaching.

Residues can be incorporated using a roto-tiller, a practice that increases the rate of mineralisation. Mulching residues at the surface of the soil is another approach, but its effects are not yet fully understood.

5.7 Choice of crop

An appropriate choice of crop, particularly in the case of a late crop, can help prevent nitrate leaching. Late crops with deep roots, such as Brussels sprouts, are especially effective at taking up nitrate from deep in the soil profile. Residues of crops such as leeks and spinach release nitrogen very quickly and may increase the risk of nitrate leaching with fall precipitation.

In certain countries, producers located near drinking water sources are obliged by law to plant certain crops as a means of reducing the risk of groundwater pollution.

5.8 Irrigation

The volume of water released during irrigation periods must be carefully managed. A soil saturated with water or a storm will inevitably lead to leaching. Excessive irrigation over a short period of time should also be avoided.

5.9 Sub-optimal nitrogen fertilisation

Sub-optimal nitrogen fertilisation prevents leaching through the reduction of mobile nitrogen in the soil. This practice tends to reduce not only the safety margin in the soil, but also the yield. For example, if the nitrogen input is reduced by 20%, the quantity of leachable nitrates is also reduced, but a 15% reduction in yield can also be expected.

Crops exhibit differing yield responses to a reduction in nitrogen input (Table 16). Yield is not the only quality to consider when deciding whether to fertilise at a sub-optimal level. Quality is often affected. A decrease in chlorophyll

Table 16: Potential yield reduction from fertilising according to a 20% reduction in N_{min} target value during sub-optimal nitrogen fertilisation to limit tissue nitrate levels

Crop	Rooting depth (cm)	Nmin target value (kg N/ha)	Nmin target value reduced by 20% (kg N/ha)	Yield using reduced Nmin target value %
Beets	60	250	200	84
Broccoli	60	300	240	90
Brussels sprouts	90	250	200	90-93
Cabbage, Savoy	90	350	280	80-85
Cabbage, white	90	350	280	83
Carrot	60	100	80	90-95
Cauliflower	60	300	240	86
Celery	60	220	175	95-98
Leeks	60	220	175	90
Lettuce, leaf	30	140	110	86
Lettuce, Boston	30	140	110	90
Spinach	30	220	175	82

Adapted from Scharpf, 1991

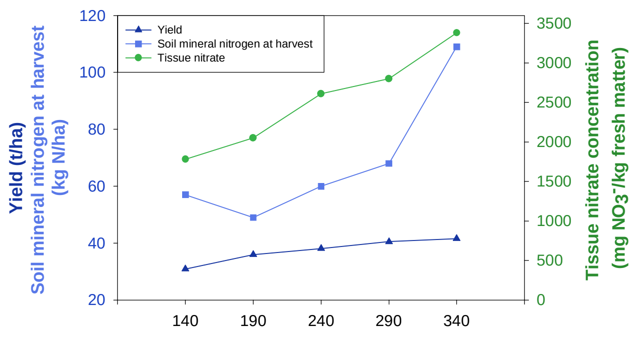
caused by low nitrogen fertilisation in crops of spinach, kohlrabi, lettuce or Brussels sprouts may cause marketing problems. Merchants do not tend to buy produce that differs from what the consumer has come to expect. By the same token, low nitrate levels, and elevated sugar and vitamin C concentrations associated with a reduction in nitrogen input are considered good qualities in produce. Farmers must balance the ill effects with the benefits when using sub-optimal fertilisation to produce a quality product that is still appealing to the consumer's eye.

The use of sub-optimal fertilisation to prevent leaching is a very new approach, and has not yet become an accepted practice. Lower yields mean lower returns for the farmer. Crop insurance or stabilisation programmes are not yet ready to offer any financial compensation for decreased yield to farmers whose lands are located in water conservation areas. In light of the financial burdens placed on farmers who fertilise sub-optimally, and the lack of incentive to reduce nitrate leaching, it is difficult to recommend sub-optimal fertilisation as a viable alternative.

In certain cases, however, the decision to fertilise sub-optimally may be quite simple. When yield remains relatively constant while nitrate levels in both the soil and tissues increase fertiliser can often be reduced with little sacrifice in yield (Figure 20).

Figure 20

Relationships among nitrogen supply, yield, tissue nitrate level and soil mineral nitrogen at harvest in sugar beet production



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6 Reduction of nitrates in the edible parts of vegetables

Over the past few decades, some controversy has arisen over the health effects of nitrate consumption. Recent studies have not been able to confirm the formerly found link between nitrate consumption and cancer through the formation of carcinogenic nitrosamines.[8, 9,10,11] While theoretically possible, it seems now appears that consuming vegetables high in nitrate may not lead to the formation of nitrosamines in the saliva or in the digestive tract. In fact, ingesting nitrate may enhance certain immune responses to microbial pathogens, in addition to causing some other minor beneficial effects.[6,7] However, cancer is a very serious subject, and it bears reiterating that the possibility that certain cancers are linked to high nitrate diets has not been conclusively rejected. A diet low in nitrate can therefore only be recommended on the principle of "better safe than sorry."

Because nitrate levels are higher in leaves and stalks than in fruit, vegetables harvested primarily for their leaves should be produced and monitored with care. Some countries, such as the Netherlands, have strict standards governing nitrate levels in leafy vegetables such as lettuce. Various factors affect nitrate levels in vegetables, and the producer can play a key role in reducing nitrate levels.

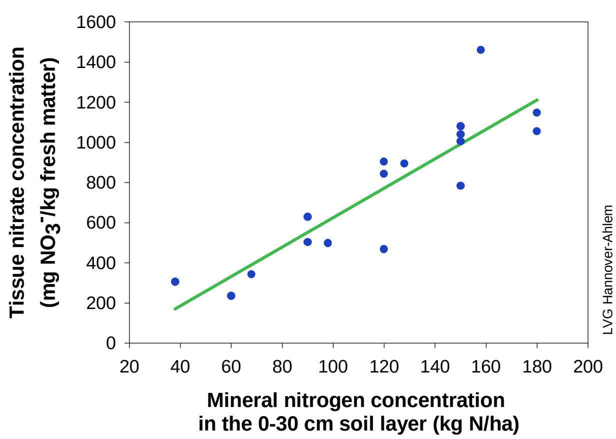
6.1 Factors influencing the nitrate in edible parts of vegetables

6.1.1 Fertilisation

While yields eventually reach a maximum despite increases in nitrogen fertiliser, nitrate levels in vegetables continue to rise. The nitrate is not used by the plant for structural use or incorporated into chlorophyll and other compounds. It remains stored in the leaf tissues in nitrate form. The availability of nitrogen in the soil influences the nitrate levels in crops such as head lettuce (Figure 21). Farmers should aim to fertilise crops at levels that do not permit this luxury consumption of nitrate. Since excess nitrate does not contribute to yield, it is of no cost-advantage for the farmer to allow it, and in fact, it is a cost-disadvantage.

Figure 21

Effect of soil mineral nitrogen on the tissue nitrate concentration of iceberg lettuce



6.1.2 Sunlight

The edible product of a crop that has received many hours of sunlight generally contains lower nitrate levels than those of a crop that has received little sun (Table 17). The reason for this is simple: sunlight stimulates the conversion of nitrates to organic compounds.

6.1.3 Variety

Plant variety can influence the nitrate levels of vegetables. Different varieties or cultivars of the same crop may have differing abilities to accumulate nitrate, or different rates at which it is converted to organic components.

6.2 Maturity at harvest

Plants that are mature contain lower levels of nitrate than those that are not. For this reason, plants that are harvested at immature stages, such spinach, have very high levels of nitrate.

6.3 Controls

Farmers are highly skilled stewards of the land. They decide on the cultural practices that are used to produce vegetables, so to a great extent, they are the ones that influence the quality of our food. Reducing the toxic health risks and environmental hazards of high nitrate levels in vegetables is within their power. Fortunately, many of the methods for reducing nitrate levels in vegetables are equally effective in reducing the risk of nitrate leaching.

6.3.1 Avoid over-fertilisation

An optimal amount of fertilisation is preferable to over-fertilisation. The relationship between nitrogen fertilisation and nitrate content of vegetables (Table 18) suggests that if care is taken to avoid over-fertilisation, the amount of nitrate present in vegetables can be reduced.

6.3.2 Sub-optimal nitrogen fertilisation

In countries where nitrate levels in vegetables are regulated, there may be no alternative to sub-optimal fertilisation and the accompanying possibility of reduced yield. Beet is a crop that is naturally high in nitrate. In some countries, regulations limit the nitrate level of beet to 3000 mg per kg of fresh beets. In reality, this can only be accomplished by using less fertiliser than required for maximal yield. Some studies conducted in Germany looked at fertilisation in white cabbage (Figure 22). Only1000 mg of nitrate per kg of fresh cabbage is allowed in the edible portion according to regulation. To achieve this goal, the amount of nitrogen supplied to the crop must be reduced to 350 kg, at the expense of 10% of the yield. Declines in yield often accompany sub-optimal fertilisation to meet regulation standards (Table 19).

Figure 22

Effect of soil mineral nitrogen on relative yield and tissue nitrate concentration in cabbage

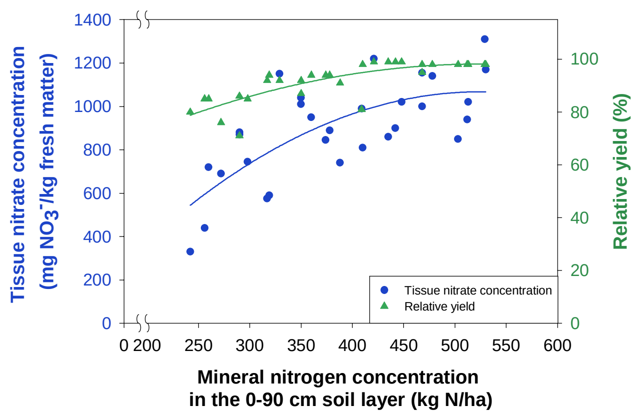


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Table 17: The relationship between sunlight and tissue nitrate concentration of sugar beets at five different rates of nitrogen fertilisation

Year	Sunlight (kWh/m^2)	Yield (t/ha)	Tissue nitrate concentration (mg NO_3^-/kg fresh matter)				
			Available nitrogen (Residual soil nitrogen in spring + fertilisers) (kg N/ha)				
			125	185	245	305	365
1984	93	42.5	2000	2350	2750	3000	3450
1985	72	60.0	400	640	1010	1790	1820

Adapted from Scharpf, 1991

Table 18: The effect of nitrogen fertilisation rate on the nitrate concentration in the tissues of several vegetables

Nitrogen fertilisation (kg N/ha)	Tissue nitrate concentration (mg NO_3/kg fresh matter)			
	Cauliflower	Kohlrabi	Lettuce	Carrots
0	26-154	47-307	150-718	104-335
75	-	-	490-1980	-
100	-	122-627	-	220-540
150	-	-	844-2799	-
200	109-416	381-1117	-	251-613
400	208-549	-	-	-

Scharpf, 1991

Table 19: Decline in yield associated with limiting tissue nitrate vegetables in some vegetable crops to 1000, 2000, 3000 or 4000 mg/kg fresh matter

Crop	Decline in yield (%)			
	Nitrate threshold (mg/kg fresh matter)			
	1000	2000	3000	4000
Beet	30	20	10	0
Cabbage, Chinese	30	0	0	0
Cabbage, white	10	0	0	0
Endive	2	0	0	0
Lettuce, leaf	70	40	0	0
Lettuce, Boston	14	0	0	0
Radish	50	0	0	0
Spinach	40	10	10	0

Scharpf and Wehrmann, 1991

6.3.3 Multiple applications of fertilisers

One technique for reducing nitrate in vegetables involves making the initial application of split nitrogen applications larger than subsequent ones. This recommendation is intended to reduce the quantity of nitrates in the edible parts of the plant, but may cause groundwater pollution if heavy rains follow the first application. Caution should be exercised when adopting this approach.

6.3.4 Ammonium fertilisers

Using ammonium fertilisers with nitrification inhibitors impedes ammonium-nitrate conversion in the soil by inhibiting the microorganisms that carry out nitrification. The result is that ammonium is directly assimilated by the plant. A concentrated, side-dressed application of ammonium fertiliser close to the plants is relatively resistant to nitrification, and delivers ammonium directly to the roots of the plants.

6.3.5 Slow-release fertilisers

Several experiments have shown that nitrate content in vegetables grown using slow-release fertilisers is lower than when using conventional fertilisers. These slow-release fertilisers ensure a better distribution of nitrogen throughout the growing season and reduced availability at the end of the season.

6.3.6 Harvest

To reduce nitrate levels in edible plant parts, harvesting should be done, whenever possible, after several hours of sunlight, and tissues that collect the highest levels of nitrate should be excluded when possible. For example, the petioles of a spinach crop are much higher in nitrate than the leaves. Avoiding the petioles will result in a crop with lower levels of nitrate, but may result in reduced yields.

7 Conclusion

Nitrogen fertilisation is an important aspect of vegetable production. When nitrogen is inadequate, plants have poor yield. This leads farmers to use large amounts of nitrogen fertiliser on vegetable crops. The difficulty, when fertilising with nitrogen, is determining how much is enough to obtain optimal yield, but not too much, which leads to serious ecological and health repercussions. Furthermore, many vegetable crops accumulate excess nitrate in their tissues, levels that may be regulated by governments. The farmer is left with this difficult balancing act. This report has suggested how this act may be accomplished, through determining optimal nitrogen fertilisation rates and applying farming practices that reduce leaching, and reduce nitrate levels in vegetables.

Appendix I

Method for Soil Nitrate Extraction and Quantification Using the Nitrachek 404 Reflectometer

Introduction:

Under normal conditions, 90% of the mineral nitrogen in the soil is in the form of nitrate (NO_3^-). This nitrate nitrogen should be considered in the decision to apply nitrogen fertiliser and how much. The use of a rapid test to detect nitrate levels in the soil represents a valuable tool for gaining timely information about the soil about to be fertilised.

Warning!

Rapid tests of soil nitrate contents are remarkably sensitive. The accuracy of the results, however, is directly proportional to the care taken in sampling and performing the analyses. It is important to carry out all the procedures and techniques with great care, and in an identical manner for all samples so that the results from different samples can be compared with one another.

Special care of solutions and test strips:

- Ensure that solutions and strips do not become contaminated.
- Be careful to not unnecessarily expose either the solutions or the test strips to air and dust.
- Store test strips in the cold, and do not use them after their ware dates.
- Hermetically seal the test strip storage tubes immediately after removing the strips from them.
- Once a tube of strips has been opened, store it in a dry place at room temperature.

Materials:

- Cordless Dewalt 14.4 Volt Versa-Clutch drill with ½-inch auger bit
- Plastic bags
- Cooler and freezer packs
- Nitrachek 404 (with 9 V battery)
- Merckoquant #10020 Nitrate test strips (Geneq)
- Extract solution (with chloride) #514730 – 10 packets (Geneq)
- Standard solution of 10 ppm Nitrate-N (with chloride) #140301-04 – 125 ml (Geneq)
- Enrichment solution of 1000 ppm KNO_3 (refrigerated)
- Distilled water or de-ionized water
- 50-ml Falcon tubes with 5-ml graduation
- Precision balance
- Whatman #1 filters, 11cm diameter
- Oven maintained at 105°C

Soil sampling:

1. Take 10 to 12 random ½-inch diameter sub-samples per plot.
2. Each sub-sample core should be taken to a depth of 30 cm or 60 cm depending on the rooting depth of the crop
3. Discard the top 1 cm of each core.
4. Mix the 10 to 12 sub-samples thoroughly in a plastic bag (about 400 ml of soil altogether).
5. Label the bag with the plot number, the depth of the sample, and the date of sampling.
6. Protect the samples from heat and light by placing them in a cooler with freezer packs.
7. Proceed with the nitrate extraction the same day, or freeze the samples as quickly as possible.

Preparation of solutions:

KNO_3 solution (1000 ppm)

Frequently the level of nitrate in the soil is too low to be quantified. Levels of less than 5 ppm appear on the Nitrachek meter as "LO" and are unusable. To avoid this, a step of nitrate enrichment of samples has been added to the process. A calculation can be made to the measured value to subtract the level of enrichment, leaving only the level of nitrate in the sample.

1. Dissolve 7.2 g KNO_3 (99.9% pure) in 1 litre of distilled water

Extraction solution

1. Pour the contents of one packet of "Extracting Power Packet with Chloride into a 500-ml volumetric flask.
2. Add 3 ml of 1000-ppm KNO_3 (equivalent of 6 ppm NO_3^--N).
3. Add distilled water to make 500 ml.
4. Stir well.

Soil sample preparation:

Extraction:

1. Pour exactly 30 ml of extraction solution into a Falcon tube.
2. Tare the solution and tube in a beaker.
3. Add 10 ml of sieved soil to the solution by adding soil until the solution reaches the 40-ml graduation. It is important to add well-mixed soil that is representative of the entire sample.
4. Note the mass of soil added (**A**).
5. Close the Falcon tube.
6. Vigorously shake the tube for two minutes and then let sit for two hours at room temperature.

Filtration:

Ten minutes before the end of the two hour waiting period, place a Whatman #1 filter paper (11 cm diameter) folded in eighths into the Falcon tube containing the liquid so that the filter paper presses the soil toward the bottom and a level of at least 5 mm of clear solution rises above the filter paper.

Quantification of NO_3^-:

- Remove the test strips and standard solution from the refrigerator at least 30 minutes prior to use.

Preparing the meter for use:

Before beginning a series of readings, always verify that the meter is working as it should, using the plastic strip supplied with the machine. This procedure can be done at any time during a series of readings, and it is a good idea to do it periodically during a long series of readings.

1. Open the "hatch" of the meter. This will turn the meter on.
2. The display should read "888" and then "CAL".
3. Make sure that the "Lot" displayed is #5.
4. Place the white side of the plastic strip face down on the reading cell, to set the meter to "0".
5. Close the hatch. Two beeps will sound, and the display will read, "GO".
6. Open the hatch, remove the strip and leave the hatch open.
7. After 60 seconds, place the plastic test strip grey-side down on the reading cell, and close the hatch.
8. The reading obtained should fall within the level indicated on the back of the case. If it does not, the reading cell requires cleaning.

Calibration:

- Take readings (maximum 5 readings) of the extraction solution following the steps a) to h). The average reading (**B**) will be used in the calculation of nitrate concentration.

- Take readings (maximum 5 readings) of the standard solution of 10 ppm following the steps a) to h). The average reading (**C**), will be used in the calculation of nitrate concentration.

a) Open the hatch of the meter. The display will read "888", then "CAL". Make sure that the Lot indicated on the display is #5.
b) Place a fresh test strip in the meter to set it to "0". Close the hatch. The meter will beep twice and then the display will read, "GO".

c) Remove the strip from the meter and dip it into the solution for three seconds (the length of three beeps). Remove the strip from the solution when the long beep sounds.
d) Shake the strip vigorously to remove excess liquid. This step is very important. The reactive portion of the strip must be dry. Do not touch or wipe the surface of the strip.
e) Let the test strip sit for the 60 seconds counted-down by the meter.
f) Pick up the strip during the last few seconds of the countdown (indicated by three beeps) and prepare for the final reading by inserting the strip into the meter.
g) Close the hatch only when the countdown finishes.
h) Record the reading.

Nitrate concentration:

- Take a reading from the sample. Record the result (**D**). If the reading is not within the limits of the meter (5 to 500), increase the dilution of the solution until the reading falls within the range. If the result seems irregular, re-do the extraction using a fresh portion of soil. After 12 samples, repeat the readings of the extraction solution and the standard solution.

Soil moisture:

1. Record the weight of an aluminum weighing dish (**E**).
2. Weigh approximately 30 g of soil into the weighing dish (taring the weighing dish first), and record the mass (**F**).
3. Place the soil and weighing dish in the oven and dry for 16 hours at 105°C.
4. Weigh the dried soil and weighing dish and record the mass (**G**).

Calculations:

Dry weight of soil used for extraction (X)

A* ((G – E) / F) = X

ppm NO_3^--N in the soil

(D-B) * [(30 + A – X) * (10 / C)] / X = ppm NO_3^--N in the soil

Conversion of ppm to kg NO3--N per hectare

ppm NO_3^--N in the soil * conversion factor = kg NO_3^--N / ha

ppm to kg/ha conversion factors

Depth of soil sample	Conversion factor
15 cm	1.98
17 cm	2.24
30 cm	3.96
34 cm	4.48
45 cm	5.94
51 cm	6.72
60 cm	7.92
68 cm	8.96

Appendix II

Method for Tissue Nitrate Extraction and Quantification Using the Nitrachek 404 Reflectometer

Sampling:

Because plant nitrate levels are strongly affected by light, it is best to take samples as early as possible in the morning, before the sunlight is strong. Ideally, sampling should be done before 10:00 am. Samples taken early in the morning are also likely to be saturated with water, which facilitates sap extraction.

In broad-leaf crops, the tissue collected during sampling should be the most recently fully expanded leaf. In cereal crops (and other plants in the family Poaceae) the tissue should be the section of stem closest to the ground. Take as many samples as possible, ensuring that they are representative of the whole group of plants to be sampled. When using leaves, remove the leaf-blades and keep only the midribs for the analysis. Place the plant samples in plastic bags and put them in a cool, dark place as soon as possible.

Materials:

- Garlic press
- Distilled water
- Standard solution (100 ppm NO_3^-)
- Two small beakers
- Nitrachek meter
- Test strips
- Two eyedroppers
- Knife
- Graduated cylinder (5-ml)

Sample preparation:

Extraction of sap:

1. Slice the plant parts to undergo extraction into pieces of about 0.5 cm.
2. Randomly select several of the pieces and mince them in a garlic-press, collecting the drops of sap in a clean beaker.

Dilution:

Unlike soil nitrate levels, which are often too low to be read by the Nitrachek meter, sap levels are often too high to be read by the meter. In addition, the green colour of undiluted sap can interfere with the reading. Therefore the sap may be diluted, and later a calculation can be made, involving the dilution factor, to arrive at the actual nitrate level of the sap.

Dilution should be done using distilled or de-ionized water, or tap water may be used provided a measure of its nitrate level is taken, to be deducted from readings of the sap nitrate levels.

25-fold dilution

1. Using an eyedropper, take two drops of sap from the beaker and place them in a second, clean beaker.
2. Add 48 drops of distilled water.
3. Stir well.

Note: When diluting many samples, it may be more efficient to measure the volume of 48 drops in a 5 ml graduated cylinder and to subsequently add this volume of water to the samples instead of counting 48 drops every time. However, the drop size may vary with different eyedroppers, and can be influenced by atmospheric pressure changes, so when changing eyedropper or if pressure changes are suspected, 48 drops should be re-measured in the graduated cylinder, and the new volume used.

50-fold dilution

If the Nitrachek meter cannot read the concentration of nitrate after 25-fold dilution, make a 50-fold dilution of the sample.

1. Using an eyedropper, take two drops of sap from the beaker and place them in a second, clean beaker.
2. Add 98 drops of distilled water.
3. Stir well.
4. Be sure to rinse and dry beakers, and rinse the inside of the eyedroppers before beginning a new sample.

Note: The extracts can be frozen for later use.

Quantification of NO_3^-:

- Remove the test strips and standard solution from the refrigerator at least 30 minutes prior to use.

Preparing the meter for use:

Before beginning a series of readings, always verify that the meter is working as it should, by using the plastic strip supplied with the machine. This procedure can be done at any time during a series of readings, and it is a good idea to do it periodically during a long series of readings.

1. Open the hatch of the meter. This will turn the meter on.
2. The display will read “888” and then “CAL”.

3. Make sure that the Lot displayed is #5.
4. Place the white side of the plastic strip face down on the reading cell, to re-set the meter.
5. Close the hatch. Two beeps will sound, and the display will read, “GO”.
6. Open the hatch, remove the strip and leave the hatch open.
7. After 60 seconds, place the plastic test strip grey-side down on the reading cell, and close the hatch.
8. The reading obtained should fall within the level indicated on the back of the case. If it does not, the reading cell requires cleaning.

Calibration:

- Take readings (maximum 5 readings) of the standard solution of 100 ppm NO3-, following the steps a) to h). The average reading (**C**) will be used in the calculation of nitrate concentration.

a) Open the hatch of the meter. The display will read “888”, then “CAL”. Make sure that the Lot indicated on the display is 5.
b) Place a fresh test strip in the meter to set it to “0”. Close the hatch. The meter will beep twice and then the display will read, “GO”.
c) Remove the strip from the meter and dip it into the solution for three seconds (the length of three beeps). Remove the strip from the solution when the long beep sounds.
d) Shake the strip vigorously to remove excess liquid. This step is very important. The reactive portion of the strip must be dry. Do not touch or wipe the surface of the strip.
e) Let the test strip sit for the 60 seconds counted-down by the meter.
f) Pick up the strip during the last few seconds of the countdown (indicated by three beeps) and prepare for the final reading by inserting the strip into the meter.
g) Close the hatch only when the countdown finishes.

- Calibration should be done after every 12 samples.

Nitrate concentration in sap extract:

- Take a reading from the sample extract. Record the result (**D**). In the case of triplicate samples, D represents an average of the three readings ($D_1 + D_2 + D_3 / 3$) If the reading is not within the limits of the meter (5 to 500), increase the dilution of the solution until the reading falls within the range.

Calculation:

The reading on the display of the meter is a relative measure that must be corrected using the calibration reading and the dilution factor.

Nitrate level in sap = (D * 100 / C) * dilution factor (i.e. 25 or 50)

8 References

[1] Lewis, O. 1986. Plants and Nitrogen. London: Edward Arnold, 104 pp.

[2] Everaarts, A.P. 1994. Nitrogen fertilization and head rot in broccoli. Netherlands Journal of Agricultural Science. 42: 195-201.

[3] Rahn, C.R., Paterson, C.D. and Vaidyanathan, L.V.V. 1993. Improving the use of nitrogen in *Brassicae* rotations. Acta Horticulturae. 339: 207-218.

[4] Sorenson, J.N., Johansen, A.S. and Poulsen, N. 1994. Influence of growth conditions on the value of crisphead lettuce: 1. Marketable and nutritional quality as affected by nitrogen supply, cultivar and plant age. Plant Foods for Human Nutrition Dordrecht. 46(1): 1-11.

[5] Babik, I., Rumpel, J. and Elkner, K. 1996. The influence of nitrogen fertilization on yield, quality and senescence of Brussels sprouts. Acta Horticulturae 407: 353-359.

[6] Duncan, C., Li, H., Dykhuizen, R., Frazer, R., Johnston, P., McKnight, G., Smith, L., Lamza, K., McKenzie, H., Batt, L., Kelly, D., Golden, M., Benjamin, N. and Leifert, C. 1997. Protection against oral and gastrointestinal diseases: Importance of dietary nitrate intake, oral nitrate reduction and enterosalivary nitrate circulation. Comparative Biochemistry and Physiololgy Part A Physiology 118(4): 939-948.

[7] McKnight, G.M., Duncan, C.W., Leifert, C. and Golden, M.H. 1999. Dietary nitrate in man: friend or foe? British Journal of Nutrition 81(5): 349-358.

[8] Cantor, K.P. 1997. Drinking water and cancer. Cancer Causes and Control 8(3): 292-308.

[9] Barrett, J.H., Parslow, R.C., McKinney, P.A., Law, G.R. and Forman, D. 1998. Nitrate in drinking water and the incidence of gastric, esophageal, and brain cancer in Yorkshire, England. Cancer Causes and Control 9(2): 153-159.

[10] van Loon, A.J., Botterweck, A.A., Goldbohm, R.A., Brants, H.A., van Kleveren, J.D. and van den Brandt, P.A. 1998. Intake of nitrate and nitrite and the risk of gastric cancer: a prospective cohort study. British Journal of Cancer 78(1): 129-35.

[11] van Leeuwen, J.A., Waltner-Toews, D., Abernathy, T., and Shoukri, M. 1999. Associations between stomach cancer incidence and drinking water contamination with atrazine and nitrate in Ontario (Canada) agroecosystems. International Journal of Epidemiology 28(5): 836-840.

[12] Babik, I., Rumpel, J. and Elkner, K. 1996. The influence of nitrogen fertilization on yield, quality and senescence of Brussels sprouts. Acta Horticulturae 407: 353-359.

[13] Malhi, S.S. and Nyborg, M. 1986. Increase in mineral N in soils during winter and loss of mineral N during early spring in north-central Alberta. Canadian Journal of Soil Science 66: 397-409.

[14] Rahn, C.R., Greenwood, D.J. and Draycott, A. 1996. Prediction of nitrogen fertilizer requirement with HRI WELL_N Computer Model. In: Progress in Nitrogen Cycling. Proceedings of 8th Nitrogen Fixation Workshop, University of Ghent, 5-8 September 1994. pp. 255-258.

[15] Lorenz, H.-P., Schlaghecken, J., Engl, G. Maync., A. and Ziegler, J. 1989. Ordnunsegemässe Stickstoff-Versorgung im Freiland-Gemüsebau—KNS-System. Mainz; Ministerium für Landwirtshaft, Weinbau und Forsten Rheinland Pfalz, 85 pp.

[16] [CPVQ] Conseil des productions végétales du Québec inc. 1996. Grilles de reference en fertilization. 2nd Edition. Agdex 540.

[17] Whitmore, A.P. and Groot, J.J.R. 1994. The mineralization of N from finely or coarsely chopped crop residues: measurements and modelling. European Journal of Agronomy 3(4): 367-373.

[18] Guérette, V., Béléc, C., Tremblay, N., Weier, U. and Scharpf, H.-C. 2000. N contribution from mineralization of vegetable crop residues. In: Proceedings of the International Society of Horticultural Science Workshop: Toward an Ecologically Sound Fertilisation in Field Vegetable Production. September 11-14, Wageningen, The Netherlands.

[19] Government of Québec. 1997. Reduction of pollution from agricultural sources. [Q-2, r. 18.2] D.742-97.

[20] [CREAQ] Le comité de références économiques en agriculture du Québec. 1995. Fumier de ferme; Valeur fertilisante. Agdex 538. Québec; Groupe Géagri, Inc.

[21] Christen, A.-M. 1997. Quelques notions de fertilisation. Québec; Ministère de l'Agriculture, des Pêcheries et de l'alimenation du Québec and Union des producteurs agricoles. 27 pp.

[22] Gagnon, B. and Berrouard, S. 1994. Effects of several organic fertilizers on growth of greenhouse tomato transplants. Canadian Journal of Plant Science 74: 167-168.

[23] Choi, J.M. and Nelson, P.V. 1996. Developing a slow-release nitrogen fertilizer from organic sources. III. Isolation and action of a feather-degrading actinomycete. 121(4): 639-643.

[24] [NADP] National Atmospheric Deposition Program. 2000. Nitrogen in the Nation's Rain. Access date: 06/03/01. http://nadp.sws.uiuc.edu/lib/brochures/nitrogen.pdf

[25] Scheffer, P. and Schachtschabel, F. 1989. Lehrbuch der Bodenkunde 12. Auflage. Stuttgart; Ferdinand Enke Verlag.

[26] Weier, U. 1992. Effect of splitting N fertilizer on yield of broccoli. Versuche in Deutschen Gartenbau. No. 26.

[27] Nitrates Committee. Engrais verts et nitrates. Communiqué No. 32. Gembloux, Belgium. 3pp.

[28] Council for Agricultural Science and Technology. 1992. Water Quality: Agriculture's Role, Part 5 of 6. In: Water Quality: Agriculture's Role. Task Force Report, No. 120. Access date: 31/08/00. http://www.inform.umd.edu/EdRes/Topic/AgrEnv/ndd/watermgt/WATER_QUALITY_AGRICULTURES_ROLE_PART_5_OF_6.html

[29] Gysi, C. 1994. Wasser- und Stickstoff-verlagerung im Jahresverlauf. Agrarforschung 1(4): 173-178.

[30] Morris, D.T. and Stevenson, C.K. 1997. Nitrogen fertilizer materials for field crops. Ontario Ministry of Agriculture, Food and Rural Affairs Factsheet #542. Access date: 14/08/00. http://www.gov.on.ca/OMAFRA/english/crops/facts/90-201.htm

[31] Rahn, C., Vaughan, A., Ramos, C., Fink, M., Gysi, C., Riley, H., Elia, A. and De Neve, S. 1997. Computer models as research tools for field vegetable crops. Inter-laboratory visit – Horticultural Research International, Wellesbourne, UK. 12-14 November 1997. Access date: 06/03/01. http://www.hri.ac.uk/enveg/lab/wellesbourne.htm

[32] Guttormsen, G. and Riley, H. 1996. Testing a nitrogen advisory model for vegetables. Acta Horticulturae. 428: 205-214.

[33] Goodlass, G., Rahn, C., Shepherd, M.A., Chalmers, A.G. and Seeney, F.M. 1997. The nitrogen requirement of vegetables: Comparisons of yield response models and recommendation systems. Journal of Horticultural Science. 72(2): 239-254.

[34] Hartz, T.K., Bendixen, W.E. and Wierdsma, L. 2000. The value of presidedress soil nitrate testing as a nitrogen management tool in irrigated vegetable production. HortScience 35(4): 651-656.

[35] University of Minnesota. 1996. Nitrate test offers economic, environmental benefits for potato farmers. News information, Minnesota's Future. No. 64.

[36] Coulombe, J., Villeneuve, S., Béléc, C. and Tremblay, N. 1999. Evaluation of soil and petiole sap nitrate quick tests for broccoli in Québec. Acta Horticulturae 506: 147-152.

[37] Berry, D. and Thicoipe, J.-P. 1993. Le test azote: un outil fiable pour le pilotage de la fertilisation azotée en cultures légumières. Acta Horticulturae 354: 125-132.

[38] Delgado, J.A. and Follett, R.F. 1998. Sap test to determine nitrate-nitrogen concentrations in aboveground biomass of winter cover crops. Communications in Soil Science and Plant Analysis 29(5&6): 545-559.

[39] Errebhi, M., Rosen, C.J. and Birong, D.E. 1998. Calibration of a petiole sap nitrate test for irrigated "Russet Burbank" potato. Communications in Soil Science and Plant Analysis 29(1&2): 23-35.

[40] Bierman, P., Wall, T. and Fuhrmann, L. 1999. Quick-tests to monitor plant N & K status and manage fertilizer applications. Access date: 31/08/00. http://www.ag.ohio-state.edu/~prec/soil/ovpgsum.htm

[41] Piekielek, W. P. and Fox, R.H. 1992. Use of a chlorophyll meter to predict sidedress nitrogen requirements for maize. Agronomy Journal 84(1): 59-65.

[42] Scharpf, H.-C. and Wehrmann, J. 1991. Nitrat in Grundwasser und Nahrungspflanzen. AID-Heft 1136. Bonn; Auswertungs-und Informationdienst für Ernährung, Landwirstschaft und Forsten e.V.

[43] Lorenz, H.-P., Schlaghecken, J., Engl, G. Mayncִ., A. and Ziegler, J. 1989. Ordnunsegemässe Stickstoff-Versorgung im Freiland-Gemüsebau—KNS-System. Mainz; Ministerium für Landwirtshaft, Weinbau und Forsten Rheinland Pfalz, 85 pp.

[44] Duval, Jean. 1995. Le rôle des légumineuses dans la pollution par les nitrates. Ecological Agriculture Projects. Access date: 1999. http://www.eap.mcgill.ca/AgroBio/ab310-08.htm

[45] Canadian Pediatrics Society, Dieticians of Canada and Health Canada. 1988. La nutrition du nourrisson né à terme et en santé. Access date: 1999. http://www.cybercable.tm.fr/~biblioa/nutrition_nourrisson.html

[46] Reynolds, W.D., Campbell, C.A., Chang, C., Cho, C.M., Ewanek, J.H., Kachanoski, R.G., MacLeod, J.A., Milburn, P.H., Simard, R.R., Webster, G.R.B. and Zebarth, B.J. 1995.Contamination agrochimique des eaux souterraines. In: Acton, D.F. and Gregorich, L.J. (eds.) La santé de nos sols. Centre de recherches sur les terres et les ressources biologiques, Agriculture et Agroalimentaire Canada. Publication 1906/F. Access date: 03/03/01. http://res.agr.ca/CANSIS/PUBLICTION/HEALTH/~chap10-4.htm

[47] Batal, K.M., Bondari, K., Granberry, D.M. and Mullinix, B.G. 1994. Effects of source, rate, and frequency of N application on yield, marketable grades and rot incidence of sweet onion (*Allium cepa* L. cv. Granex-33). Journal of Horticultural Science 69: 1043-1051.

[48] Brewster, J.L. and Butler, H.A. 1989. Effects on nitrogen supply on bulb development in onion *Allium cepa* L. Journal of Experimental Botany 40(219): 1155-1162.

[49] Liptay, A., Jewett, T.J., Tan, T.J., Drury, C. and van Wesenbeeck, I. 1997. Effect of fertigation on processing tomato production in two sandy loam soils. Acta Horticulturae. 449(1): 349-353.

[50] Rowse, H.R. 1988. Starter fertilizer and insecticide injection from the seed drill. The Grower 110: 22-24.

[51] Hoyt, G.D., Sanders, D.C., Garrett, J.T., Batal, K.M., Davis, J.M., Decoteau, D.R. and Dufault, R. J. 1994. Nitrate movement in southeastern coastal plain soils under conservation-tilled vegetable production. In: Bauer, P.J. and Busscher, W.J., (eds.). Proceedings of the 1994 Southern Conservation Tillage Conference for Sustainable Agriculture. Columbia, South Carolina, USA. pp.120-123.

[52] Varvel, G.E. and Peterson, T. 1992. Nitrogen fertilizer recovery by soybean in monoculture and rotation systems. Agronomy Journal 84(2): 215-218.

[53] Gangbazo, G. 2000. Relations empiriques entre les utilisations du territoire agricole et la qualité de l'eau des rivières. Vector environnement. 33(2): 42-49.

[54] Demarais, G., and Breune, I. 1998. Diagnostique agro-environnemental de la tête du bassin versant du ruisseau Corbin. Québec; Centre de Développement d'Agrobiologie. 37 pp.

References for tables and figures

Barton, L., McLay, C.D.A., Schipper, L.A. and C.T. Smith. 1999. Annual denitrification rates in agricultural and forest soils: A review. Australian Journal of Soil Research 37: 1073-1093.

Demarais, G., and Breune, I. 1998. Diagnostique agro-environnemental de la tête du bassin versant du ruisseau Corbin. Québec; Centre de Développement d'Agrobiologie. 37 pp.

LVG Hannover-Ahlem
Results of experiments done at the Horticulture Research Station (LVG) Hannover-Ahlem in Lower Saxony, North Germany. The experiments were carried out between 1980 and 1997 under the direction of H.C. Scharpf and U.Weier by the research station team supported by students of the University of Hannover (diploma theses). Diploma theses are not published in accessible journals. The results are part of the official advisory system in Germany. For more detailed information contact:
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Malhi, S.S. and Nyborg, M. 1986. Increase in mineral N in soils during winter and loss of mineral N during early spring in north-central Alberta. Canadian Journal of Soil Science 66: 397-409.

Scharpf, H.-C. 1991. Stickstoffdünung im Gemüsebau. AID-Heft 1223. Bonn; Auswertungs-und Informationdienst für Ernährung, Landwirstschaft und Forsten e.V.

Scharpf, H.-C. and Wehrmann, J. 1991. Nitrat in Grundwasser und Nahrungspflanzen. AID-Heft 1136. Bonn; Auswertungs-und Informationdienst für Ernährung, Landwirstschaft und Forsten e.V.

Schrage, R. 1990. Methoden zur Bestimmung des Stickstoff-Düngerbedarfs von Gemüsekulturen mit geringem analytischen Aufwand. University of Hannover Doctoral Thesis.