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Nutrient and Fertilizer Management in Field Grown Vegetables

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Introduction

Vegetables are mostly high value crops and small yield losses due to imperfect mineral nutrition, which would be difficult to measure in a field experiment, can result in a substantial loss of profit. If this is to be avoided, the grower must use every means at his disposal to optimise nutritional practices, and this is most likely to be achieved by a thorough understanding of the principles involved.

Very often, vegetable growers are forced by the market to achieve exaggerated crop standards, like very specific size and appearance, total freedom from blemishes or complete absence of pesticide residues and extremely low concentrations of nitrate, which is in fact a normal constituent of plants.

At present, questions of flavour, texture and dietary value of vegetables receive very little attention from either scientists or supermarkets but there are signs that this attitude is changing.

Finally, it has to be recognised that a successful nutrient management in vegetable growing is characterized by minimal water and air pollution. Information about the influence of mineral nutrition and fertilizer management on these factors will be given in the following chapters.

1. Economic and environmental factors governing vegetable growing

1.1. The importance of a market

In the past, the predominant factor which governed commercial vegetable growing was the proximity of a suitable market. With ingenuity and perseverence, it is possible to grow vegetables almost anywhere, although a warm sheltered site and a light, well-drained soil with a good organic matter content are desirable. The availability of a substantial labour force, primarily for the harvesting and preparation of the crop for sale, is also essential, although mechanisation of these processes is steadily increasing. At the end the the second world war, UK vegetable production was concentrated on the fringes of major towns and in certain climatically favoured areas such as the Vale of Evesham. This was no doubt the situation in most industrialised temperate countries, and it is still found in many parts of the world.

With the rapid advance of mechanisation and the use of agrochemicals, however, and the ability to deliver the produce by road, rail and plane over considerable distances, production moved more to areas where the most favourable environmental conditions for vegetable growing are found.

Meanwhile, in most industrialised countries, sale of the produce gradually switched from the greengrocer or market stall to the supermarket, and consumers, who before the fifties were accustomed to eating quite different vegetables in each season, began to expect to be offered a complete range of produce throughout the year. At first, this demand was satisfied by the processing industry, which by the establishment of canning and freezing plants, also influenced the siting of production of certain crops. However, with the growth of the "affluent society", the consumer demanded fresh produce, and supermarkets responded by importing produce, often by plane, from all over the world. These and other recent trends in the vegetable industry have been described for the UK by Wright (1994).

1.2. Temperature and geographical distribution

This world trade is a reflection of the fact that the most important climatic factor in vegetable growing, particularly for winter supplies in temperate regions, is temperature. Vegetable plants tend to be more widely spaced apart than those of arable crops and to have smaller seeds. Particularly when they are grown as direct-drilled crops, therefore, they have a long exponential growth phase when they grow at about 15-25% per day, this rate being determined by temperature rather than radiation receipt. Development is also highly temperature-dependent. The minimum temperature for growth is between 0 and about 6°C (much higher for "warm-season" species such as tomato), and the optimum is generally in the mid-20s (Table 1). An increase of 2-3°C (such as is obtained by the use of plastic covers) can have a very marked effect on maturity date, and because of the demand for year-round production of each type of produce, these effects dominate the profitability of production and influence the movement of areas of production around the world. For example, although California produces most of the summer vegetables for the USA, Florida produces them for the winter (Maynard and Locascio, 1982). In Europe, The Netherlands provides a very large share of the field-grown summer vegetables and the protected crops (tomatoes, cucumbers, peppers), whilst Spain and Italy provide much of the winter produce (Hinton, 1991). In Sweden and Finland, horticultural production is concentrated in the southernmost part of each country (Vesanto and Lehtimäki, 1993), whereas in Norway it is confined by the topography and proximity of the main markets (Balvoll, 1989).

Table 1. Temperature requirements (°C) for vegetable crops (Maynard and Lorenz, 1988).

Optimum	Minimum	Maximum	Vegetable
13-24	7	29	Chicory, chive, garlic, leek, onion, shallot
16-18	4	24	Beet, broad bean, broccoli, Brussels sprout, cabbage, kohlrabi, parsnip, radish, swede, spinach, turnip
16-18	7	24	Carrot, cauliflower, celeriac, celery, Chinese cabbage, endive, Florence fennel, lettuce, parsley, pea
16-21	10	27	French bean
16-24	10	35	Sweet corn, New Zealand spinach
18-24	10	32	Pumpkin, squash
18-24	16	32	Cucumber, muskmelon
21-24	18	27	Sweet pepper, tomato
21-29	18	35	Eggplant, chilli pepper, okra, water-melon

After the exponential growth phase, there is usually a linear phase when the growth rate is about 250 kg dry matter ha^{-1} d^{-1}, and for many species which are harvested whilst still growing, this may be the final phase (Greenwood *et al.*, 1977), although the growth of species which remain in the ground into the winter may slow down because of low temperature and lack of light. Others, notably onions, mature and stop growing as a result of ontogeny, and the same would apply to other determinate crops such as beans if they were allowed to grow beyond their normal harvesting time as green vegetables.

Whilst low temperatures often set the northern geographical limits of production (in the northern hemisphere), or an altitude limit in mountainous regions, the high temperatures (especially at night) of tropical regions mean that the "cool-season" vegetable crops traditionally grown in Europe may only be grown in the "winter", or at high altitude, in the tropics.

Another temperature-related aspect is freedom from severe frosts. For example, there are coastal zones, such as south-west England, south-west Wales, Brittany and Long Island (USA), which enjoy mild winters because of the Gulf Stream effect and are therefore used for the production of winter crops like winter cauliflower, which cannot tolerate severe frost.

1.3. Radiation and rainfall

Climatic factors other than temperature are less important in restricting production. If rainfall is at all marginal, irrigation is essential for many species. The total water requirement is determined largely by the evaporative demand of the atmosphere, and there are various systems available for calculating it, using the principles established by Penman (1948). Water quality, i.e. salinity or the toxic effects of particular elements such as boron, are not normally a problem in temperate zones, but in the semi-arid and arid subtropics and tropics, poor water quality might be a serious limitation. To manage these difficulties, the reader should refer to Lorenz and Maynard (1988).

Solar radiation is of course the prime source of energy for crop growth, and its efficient interception (for example by the use of transplanting rather than direct drilling into the field) is the key to high productivity per unit land area. However, radiation only becomes a factor limiting growth once the crop is fairly advanced, and leaves begin to shade one another (Bierhuizen *et al.*, 1973).

1.4. Soil

In general, well-drained soils such as deep silts, fine sandy loams, organic soils or strongly weathered permeable soils, are usually preferred for vegetable production because of their suitability for working at most times of the year. Clay soils are rarely used except for some brassica crops such as Brussels sprouts, and light sandy soils are favoured for root crops, particularly carrots and parsnips, which are easily harvested from such soils with minimal washing problems. Peat (muck) soils have been much used for celery, onions, carrots, and salad crops, but their extent is decreasing because vegetable growing is linked with intensive soil aeration and tillage, which accelerates unfavourable peat oxidation.

Inherent low nutrient supplying capacity of the soil and an acid soil reaction can usually be corrected. A clear example of how soils with nutrient deficiencies can be made productive in an area with favourable winter temperatures is the state of Florida, where 161 000 ha of poor soils (in places mere rock) supply the USA with most of its winter vegetable needs (Maynard and Locascio, 1982). Lime-induced iron chlorosis is much rarer in vegetables than in fruit crops, but other micronutrient deficiencies associated with high pH can be troublesome, so that alkaline soils are best avoided, except for brassica crops.

2. Principles of crop mineral nutrition

2.1. Essential elements

Plants require 12 or 13 mineral elements (Table 2) in order to grow (see Mengel and Kirkby, 1987; and Marschner, 1986 for a full description of the functions of these elements and their behaviour in soil, etc.).

If the supply of any one of these fails to keep pace with the demand, its average concentration in the plant will fall due to dilution by growth, which may slow down. In the case of certain immobile elements such as calcium and boron, new growth will exhibit symptoms of the deficiency, such as necrosis. To avoid these effects, the grower must either supplement the natural supply of nutrients from the soil with inorganic fertilizers, organic manures, or foliar feeds, or else modify it by adjusting the pH. The element most often deficient (although representing 80% of the atmosphere) is nitrogen (N), and despite the objections of the environmentalists, it is impossible to imagine world agriculture without "bag" nitrogen. Many soils also require regular additions of phosphorus (P) and potassium (K), but it is perhaps surprising that most soils continue to supply the other 9-10 elements without quickly becoming quickly exhausted.

Table 2. Essential elements for plant growth and their approximate critical concentrations (see Fig. 4) in "Youngest fully-expanded leaves" (YFEL) in mid-growth. Concentrations marked* have no diagnostic value but are simply fairly typical. Fuller details, applicable to different species, are given by Reuter and Robinson (1986).

Element	Critical concentration (in dry matter)
Nitrogen (N)	3.5 %
Phosphorus (P)	0.35 %
Potassium (K)	2.0 %
Calcium (Ca)	1.0 %*
Magnesium (Mg)	0.2 %
Sulphur (S)	0.2 % (0.35 for Crucifers)
Iron (Fe)	100 $\mu g\ g^{-1}$*
Manganese (Mn)	20 $\mu g\ g^{-1}$
Zinc (Zn)	20 $\mu g\ g^{-1}$
Copper (Cu)	5 $\mu g\ g^{-1}$
Boron (B)	20 $\mu g\ g^{-1}$
Molybdenum (Mo)	0.1 $\mu g\ g^{-1}$
Chloride (Cl)	100 $\mu g\ g^{-1}$

2.2. Capacity and intensity factors in plant nutrition

In order to understand crop demand for nutrients, it is helpful to consider a plant growing in a large tank of vigorously stirred nutrient solution. Some classical experiments (Olsen, 1950; Clement *et al.*, 1978; Williams, 1961) have shown that in such a situation, only very low concentrations (such as 0.1 mg N l^{-1}) are required to satisfy the demand of the plant. This is because the root surfaces have a powerful affinity for the nutrient ions, which are carried to them by the "mass flow" created by the stirring. If the stirring stops, a depleted zone forms around the roots, which then depend on the ion diffusing from the bulk solution to the root surface. This means that a higher concentration is then needed in the bulk solution in order the "drive" the ions down a concentration gradient, and still provide the necessary critical concentration at the root surface (Milthorpe and Moorby, 1974). In soil-grown crops, such "downhill" gradients exist for most nutrient ions at most times, except those, such as calcium and magnesium, which exist at such high concentrations in the soil solution that they are swept to the root by the mass flow of the transpiration stream faster than they are needed by the plant. These ions may actually accumulate at the root surface (Barber, 1962).

For "unbuffered" nutrients, such as nitrate, this tank analogy represents the situation in soil quite well: most of the nutrient in the rooting zone is accessible to the plant, so the total amount of nutrients measured in the soil is a good indication of availability.

However, most nutrients, notably cations such as ammonium, potassium, calcium and magnesium, are not only present in the soil solution, but are also "adsorbed" by electrical attraction, to the clay and humus particles in the soil. Some, such as phosphate and borate, may also be present as sparingly soluble salts which may enter the soil solution (and thus become available for uptake) only very slowly, and only when the pH favours their solution. These adsorbed or insoluble forms act as a "buffer" or reserve, which tends to replenish the soil solution when it is depleted of an ion by root adsorption. Those fractions of a nutrient which are dissolved in the soil solution or very readily exchangeable with it are referred to as the "labile pool" of that nutrient. The soil solution concentration, which is what the plant senses, is called the "intensity factor" whereas the reserve available for replenishing the soil solution fairly quickly is called the "quantity" or "capacity" factor. Analytical methods for these buffered nutrients usually represent the quantity rather than the intensity, but in clayey soils, this may give an overestimate of the concentration in the soil solution (see Fig. 1).

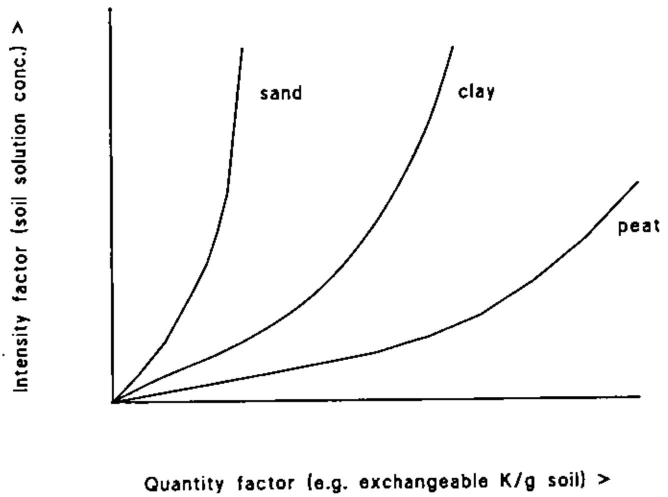

Fig. 1. Formalised quantity-intensity relationships for different soil types. In the sandy soil, the soil solution concentration is high but the quantity available to buffer it is low: clay and peat soils hold a lot of P and cations but the soil solution concentration tends to be low.

The upper concentration limit in the rhizosphere for many nutrient ions is determined by the "salt effect", i.e. the total osmotic strength of the solution, which should not exceed 1-2 bars (0.1-0.2 MPa) (Kramer, 1949). Some, such as the borate ion, may have specific toxic effects far in excess of that due to osmotic pressure (Lorenz and Maynard, 1988). The point to be made here is that the secret of optimising crop nutrition is to maintain the root surface concentration of all nutrient ions above their critical level whilst avoiding the build-up of damaging salt concentrations. The latter is aggravated by soil drying.

2.3. Consequences for field grown vegetables

From the above, it can be seen that for cations, which are adsorbed onto clay, and indeed for phosphate, which is not only adsorbed but also precipitated, it is necessary, right from the earliest stage of plant establishment, to raise the equilibrium concentration around the roots to the point where the soil solution concentration is above the critical level which they need. For phosphorus, this appears to be about 1.4 µM (0.04 ppm P) for P-efficient species, and 7 µM (0.2 ppm P) for inefficient ones (Föhse *et al.*, 1988) (see 2.4.).

This may require a substantial, albeit localised, application of the nutrient, the amount of which will depend on the adsorbing properties of the soil. Thereafter, depletion of these ions from the rhizosphere may have rather little effect on the soil solution concentration because of desorption from the exchange medium.

Because of these effects of nutrient adsorption and desorption, it is common in fertilizer experiments to see a response to buffered nutrients very early in crop life, even to high rates of application. For nitrate-N, which is not buffered by the soil, the benefit of the high rates, which at the seedling stage sometimes may retard the growth, only becomes apparent during the so-called "grand period of growth" when the crop is depleting the soil mineral N to a low concentration (Scaife *et al.*, 1986). In order to understand the timing of these effects (and hence make enlightened decisions about fertilizer placement, etc.), it is useful when doing fertilizer experiments to make weekly destructive or non-destructive estimates of plant size, and to plot their logarithms against time. In the example shown in Fig. 2, this form of plot suggested that P response was complete soon after emergence, after which plants on all P treatments grew with the same relative growth rate, although their absolute growth rate was governed by the size differences established when they were young.

It should be clear from the above that while crops are growing they exert a demand for nutrients which means that a rather high soil solution concentration is needed to drive the nutrients across the diffusion barrier to the root surface. What distinguishes many vegetable crops from most arable crops is that the former are still growing, often very fast, at the time of harvest, whereas most arable crops have stopped. Vegetable crops therefore need to be given enough fertilizer, notably N, to maintain growth at harvest time, and this is why they leave much higher residues nutrient in the soil than arable crops.

2.4. Genotypic differences in response to nutrients

Relatively little research work has been done to explain why one species or variety differs from another in its response to nutrients under field conditions. The subject has been reviewed by Barker (1989). Plant physiologists working with stirred nutrient solutions have attempted to characterise the response of different genotypes in terms of kinetic parameters. Clarkson and Hanson (1980) reviewed this approach and concluded that plants have a very high affinity for nutrients and that the amount transported is regulated largely by demand.

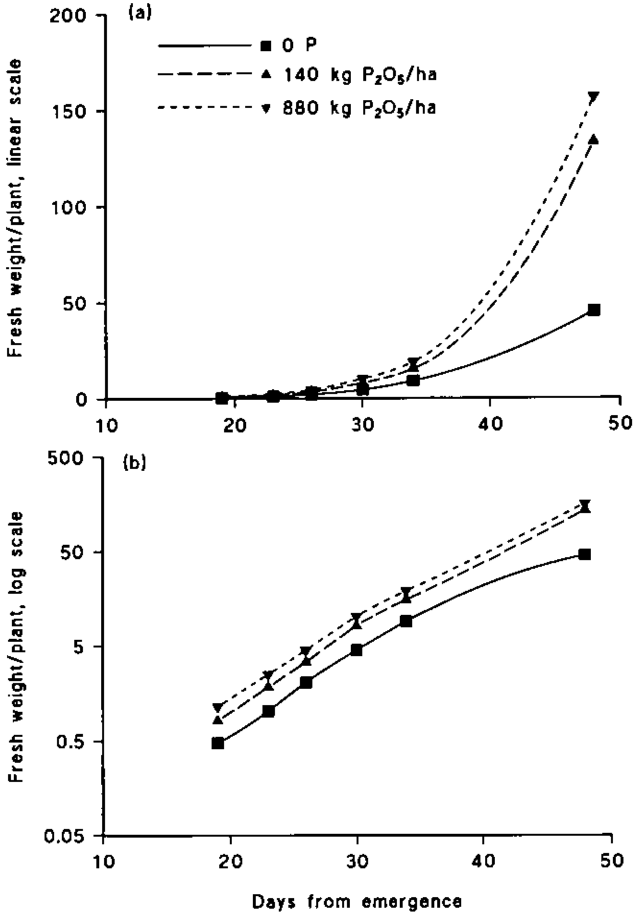

Fig. 2. Lettuce growth with 3 levels of broadcast basal P fertilizer, plotted (a) on a linear scale, and (b) on a logarithmic scale. The latter makes it clear that response occurred within 19 d of emergence (Scaife, unpublished data).

In the case of nitrogen, because of the unbuffered nature of nitrate in the soil, differences can be explained to some extent in terms of the total amount of N in the crop when it reaches physiological maturity. However, certain species seem not to fit this view: for example, the root crops, carrots, parsnips, swedes and turnips remove 150-350 kg N ha^{-1}, but are very unresponsive to applied N (NVRS, 1980; Sørensen, 1993).

One factor which might explain some such cases is the dynamics of the system: a crop requiring 100 kg N ha^{-1} over a six-month growth period might be fully satisfied by natural soil mineralization (see 4.1.1.), whereas one needing the same amount over a shorter growth period might require some extra N as fertilizer, because its needs outpace the mineralization rate.

For buffered elements, such as P and K, the dissimilarity between uptake and responsiveness is even more striking. For example, lettuce and spinach are highly responsive to P, but only take up about 16 and 30 kg P_2O_5 ha^{-1} respectively, whereas summer cabbage, which is unresponsive, takes up 50 kg ha^{-1} (Greenwood *et al.*, 1980b). Föhse *et al.* (1991) have shown that species differences in P efficiency are attributable to uptake factors such as root length or uptake rate per unit root length, rather than the amount of growth made per mg P taken up. Root hairs were the characteristic feature of efficient species. Claasen (1992) referred to work showing how acidification of the rhizosphere by the roots can influence P uptake. Variable infection by vesicular-arbuscular mycorrhizae (VAM), which infect most species apart from Cruciferae and Chenopodiaceae (Marschner, 1986), could also be relevant (Mayer *et al.*, 1989; Krikun *et al.*, 1990).

Micronutrients are normally present in soils in large quantities (relative to crop demand) but their availability to plants is limited by their solubility. For iron uptake, certain genotypes are strikingly "iron-efficient" and this efficiency is induced by iron stress and may be controlled by a single gene (Brown, 1978). Excretion of H^+ and HCO_3^- ions, which is enhanced by ammonium as opposed to nitrate uptake, is responsible for most of these "solubilizing" effects of roots (Marschner, 1986).

Breeding for efficiency of nutrient uptake is clearly worthwhile for those elements which are present in large quantities in the soil, and can be made available by root exudates, etc; it is less likely to work for unbuffered elements like nitrogen and sulphur.

NOTE

In this book, we have frequently expressed amounts of phosphorus and potassium as their oxides, P_2O_5 and K_2O, as is customary on fertilizer bags. To convert amounts or concentrations in these units to P and K, multiply by 0.44 and 0.83 respectively.

Nitrate concentrations in plants and soils are sometimes expressed as nitrate (NO_3) (e.g. by the European Union authorities) and sometimes as nitrate-N (NO_3N). To convert from the former to the latter, multiply by 0.23. The word "nitrate" should mean NO_3.

Whenever these units are discussed, it is important to make clear which form of expression is being used.

3. Diagnosis of nutrient and fertilizer requirements

3.1. Crop response to fertilizer nutrients

Field experimentation

Not enough is known about crop demand for nutrients, and their release from soil, to enable us to calculate optimal fertilizer requirements from first principles. Since fertilizers were invented in the mid-19th century, therefore, the empirical approach of experimenting in the field or with pots has been much used. The two questions which such experiments seek to answer are "which elements are deficient?" or "how much of element X should I apply?"

The first is best answered by a "factorial" experiment of 2^n design, i.e. including several nutrients, each at two levels (absent and present). For the second, at least five levels of application are needed to define the "response curve". In both cases, great attention to correct statistical technique is needed unless large responses can be expected.

Fertilizer response curves

Assuming that we have carried out a response-curve type of experiment with five or more levels of a nutrient X, recorded the yields obtained, and minimised the error (for example, by covariance on plant density), the next problem is to find the optimal level of X (giving the highest yield Y) or the economic optimum (giving the highest financial profit from the use of X). One method, not favoured by statisticians, is to simply plot Y against X, indicating the magnitude of the error calculated from the analysis of variance, and to use a flexible plastic rule to draw a smooth curve which connects the points as closely as seems to be required by the size of the error. It may be necessary to make certain rules about the shape of the curve (e.g. it should never level out and then turn upwards), and to ask an unbiased colleague to draw the curve to ensure impartiality. The horizontal tangent to the peak of the curve gives the position of the optimum on the X-axis. If the Y-axis is expressed in monetary values, and the cost of the fertilizer is shown as a straight line (Fig. 3), then the economic optimum may be found where a line parallel to this line makes a tangent to the crop response curve. With vegetable crops, it is often the case that the economic optimum is virtually the same as the optimum for yield, because of the high value of the crop compared with the cost of fertilizer.

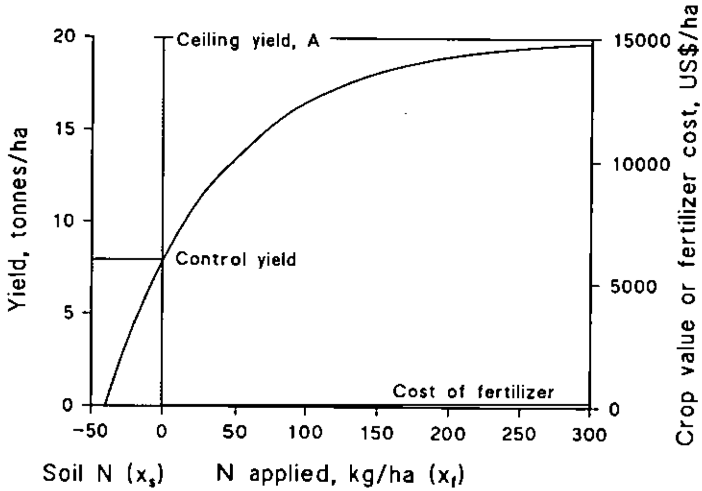

Fig. 3. Mitscherlich response curve and its use to find the optimum fertilizer dressing. The equation of the curve is $Y = A\ (1 - e^{-c(x_s + x_f)})$, where:

A is the ceiling yield when $x = \infty$, (20 t/ha),

x_f is the amount of nutrient applied,

x_s is the amount of this nutrient supplied by the soil, expressed in the same units as x_f, (40 kg/ha),

c is the "curvature term" calculated from $\frac{1}{x_i} \ln \frac{i_1}{i_2}$, (= 0.0125)

The economic optimum occurs where the slope of the response curve equals that of the cost curve, i.e. at about 300 kg/ha. Figures apply to cauliflower grown on a light soil.

The advantage of using one of the numerous mathematical equations available to define such curves (such as that of Mitscherlich, 1909) is that they provide parameter values which describe the shape of the curve (see caption to Fig. 3). If a large number of experimental results from scattered sites are available, this enables one to relate these parameter values to appropriate soil or environmental measures which may then provide a system for predicting responses over a large geographical area (Scaife, 1968).

A complication is that fertilizer response curves often show a "downturn" at high application levels. Mitscherlich observed this, and modified his equation accordingly (Mitscherlich, 1928). The downturn may manifest itself in a great variety of ways. Salt damage to emerging seedlings, including actual loss of plant stand, is common when vegetable crops are drilled into a seedbed treated with nitrate, especially in dry weather. As little as 50 kg N ha^{-1} can depress lettuce yields because of this (Page and Cleaver, 1983). This is a major reason for using split nitrogen applications.

Mitscherlich was adamant that c (the parameter describing the sharpness of curvature of his response curve) should not vary for a particular nutrient, but it is not difficult to think of reasons why it should. In the case of phosphorus, for example, we know that highly P-fixing soils require huge quantities of P (unless it is suitably placed) to reach maximum yield, whereas this is less true on non-fixing soils. For nitrogen, it is clear that if heavy rain washes a large proportion of the nitrate out of the rooting zone, a much higher initial dose will be needed to produce maximum yield than if no such leaching occurs.

Simulation models

This last example can help to explain why various workers (Scaife, 1974; Hansen *et al.*, 1993; Greenwood *et al.*, 1974) came to the conclusion that the "curve-fitting" approach to interpreting fertilizer experiments was inadequate. If the leaching event occurs shortly after the N is applied, it will obviously have a big effect on the final response, but if it occurs after the crop has absorbed most of the N, there will be little or no effect. The timing of the rainfall in relation to the stage of development of the crop is therefore important, and this suggests that a dynamic approach is needed. Indeed, consideration of the numerous nitrogen transformations taking place in the soil leads one to the same conclusion.

Another reason for needing a dynamic approach in the case of vegetable crops is that unlike most arable crops, they are often still growing rapidly at the time of harvest. For certain crops such as leeks and carrots, there is no particular moment of maturity, and the grower may wish to know whether fertilizer requirement for an early harvest is the same as for a late one. Others, such as lettuce and cauliflower, are harvested shortly before they "bolt", and the question arises as to whether the yield shortfall due to inadequate nutrition can be made good by deferring harvest for a few days (Burns, 1990). If maturity date is unaffected by crop nutrient status, it cannot. As a general rule, all field experiments with this type of vegetable crop (not merely nutritional ones) should be harvested in such a way as to provide not only the yield but also the "50% maturity date". The more objective way to find the latter is by means a of series of destructive harvests, bracketing the maturation period for all the treatments, but this greatly increases the size of the experiment. Most research workers adopt a "cut-over" policy similar to commercial practice, whereby the person cutting the heads makes a subjective judgement, either by eye or by "feel" as to whether a plant is ready to cut.

The dynamic approach means that a complex mathematical model is built up as a series of relationships connecting what the modeller considers to be relevant parts of the system. Typically, the growth of the crop (unlimited by water and nutrients) is a function of initial plant weight, density, temperature and radiation. Growth of the root system down the soil profile is simulated, although few, if any, models allow for the known adaptation of root growth to soil water and nutrient "pockets" which has been known about since 1892 (Barley, 1970). Nutrient demand is the product of the growth rate (unlimited by the nutrient) and an optimal nutrient percentage which varies with growth stage (Greenwood *et al.*, 1978). Estimating the supply is more difficult, and tends to be based on the whole rooted zone at any given moment rather than the rhizosphere. For nitrogen (which has been the main interest of these models) the various transformations, including leaching through successive layers of soil (Burns, 1974) are modelled. The computer proceeds in daily (or smaller) time-steps to update the values of each variable in the system.

Although these simulation models offer a possible solution to the complexities of crop nutrition, they also confront the modeller with a host of new problems, not least of which is that of predicting the growth curves of plants over as much as five orders of magnitude. For the user, they offer the possibility of simulating various scenarios, and perhaps of making use of the experience to plan field experiments. It is unwise to use them as a "black box": the user should find out what assumptions are built into them.

3.2. Which elements are deficient or toxic?

3.2.1. Indication of nutritional disorders

Growers and their advisers should familiarize themselves with the symptoms of nutrient deficiencies and toxicities; which are illustrated in several publications (Scaife and Turner, 1983; Sprague, 1964; Bergmann and Neubert, 1983; Wallace, 1961). Some symptoms may be confused with those of virus attack or pesticide damage, and it is important, when attempting to diagnose such problems, to visit the field concerned, to spend time talking over the various possibilities, and to confirm the diagnosis by leaf analysis, if this is appropriate. Susceptibility of species to each disorder is indicated in Table 3, together with a brief description of the symptoms. Plates 1-6 show some common deficiency symptoms.

Table 3. Nutritional disorders in vegetables and predisposing factors.

Nutrient/mineral elements	Deficiency and toxicity symptoms - Predisposing factors
Deficiency	
Nitrogen	Poor growth; pale leaves, especially old ones; pink and purple tinges on leaves and petioles of brassicas; red beet leaves deep purple and spotted; petiole or midrib "sap" nitrate concentration measured with "Merckoquant" test strips will be below 250 mg NO_3 l^{-1}. The most ubiquitous nutrient deficiency throughout the world on all but highly organic soils.
Phosphorus	Sometimes older leaves show purple tinges (on undersides for brassicas) especially in cold weather; but growth, especially of seedlings, may be severely restricted with virtually no symptom; leaf and soil analysis useful.
Potassium	Marginal scorch and upward curling of older leaves; shrivelling of old carrot, onion, and leek leaves; leaf and soil analysis useful. As for P deficiency, rarely seen because of liberal PK applications.
Calcium	Necrosis of growing point or young leaf edges (lettuce tip-burn; brassicas, internal browning of Brussels sprout buttons; blackheart of celery); leaf cupping and puckering of edges. In practice, the disorders are usually due to localised failure of calcium transport; soil analysis not useful; plant analysis only if soluble Ca measured in susceptible tissues.
Magnesium	Interveinal chlorosis (yellowing) of older leaves; sometimes leaf edges stay green (e.g. pea); red tints may move in from leaf margins (carrot, swede); or chlorosis moving in from leaf margin (celery); leaf blistering in red beet; in lettuce, chlorosis can be confused with beet western yellows virus attack: leaf and soil analysis useful.

Table 3. (continued).

Nutrient/mineral elements	Deficiency and toxicity symptoms - Predisposing factors
Deficiency	
Sulphur	May resemble nitrogen deficiency but sap nitrate concentration will be normal or high; pale colours on young rather than old leaves; in brassicas bronzing and cupping of new leaves; leaf analysis useful; soil less so. Becoming commoner as atmospheric sulphur dioxide falls.
Iron	Very rare in vegetables; whitening of young leaves, with veins remaining green initially; can occur in hydroponic systems. In soil, it may be induced by heavy metal toxicity (e.g. Cu, Ni, Zn from sewage sludge - see Archer, 1988), or if the soil is calcareous and waterlogged. Soil analysis not useful (except to indicate free $CaCO_3$ or excess heavy metals); leaf analysis for total Fe not useful; some authors (Rao *et al.*, 1987) advocate measuring ferrous iron in fresh tissue.
Manganese	Similar to magnesium deficiency but usually a finer and fainter interveinal chlorosis, often over the whole plant or especially on young leaves. Longitudinal chlorotic striping of older onion leaves. "Marsh spot" (hollows or discolouration inside seeds) of peas and beans. Common in UK, especially on peaty or organic soils above pH 6.0 or on sands above pH 6.5 (Archer, 1988). Leaf analysis very useful, but not soil.
Zinc	An important deficiency in many countries notably USA, Australia, India and in the Middle East, but much less common in Europe; causes longitudinal chlorotic striping and leaf twisting in onions, and interveinal striping leading to pure white young leaves in sweet corn ("white bud"); pitcher-shaped leaves in cabbage; aggravated by high pH, heavy P fertilization, and cool, overcast weather (Thorne, 1957). Soil (especially DTPA extraction) and leaf analysis useful (Lindsay, 1972).

Table 3. (continued).

Nutrient/mineral elements	Deficiency and toxicity symptoms - Predisposing factors
Deficiency	
Copper	Common on newly reclaimed peat soils, irrespective of pH, throughout the world; young carrot leaves dark green, do not unfold; older leaves limp; lettuce leaves elongated, chlorotic at edges, limp; onion bulbs pale with thin yellow scales (Purvis and Carolus, 1964). Soil analysis (DTPA or EDTA extract) useful; leaf analysis not so; ADAS (UK advisory service) recommends test spraying of small area of crop, which shows a response in 7-10 d (Archer, 1988).
Boron	Suspected of involvement with numerous disorders but proof is often lacking: causes death of growing point, brittleness and thickening of tissues, corky lesions on midribs, petioles, stems; transverse cracks ("cat-scratch") on petioles; brown heart of swede roots; cankerous skin and hard black lesions inside beetroots; brown or undeveloped curd on cauliflower; hollows in tissues (but see Scaife and Wurr, 1990, re. hollow stem of cauliflower). Occurs on light soils generally above pH 6.5 or recently limed, particularly in dry summers following a wet spring (Farrer, Caldwell and Archer, 1976). Soil (hot water soluble B in UK) and leaf analysis useful, though critical concentrations rather doubtful.
Molybdenum	Affects cauliflower, causing "whiptail" - leaf lamina is reduced leaving mainly midribs; lettuce occasionally affected - leaves turn pale, papery and ovate in shape, necrotic at edges; plants fail to heart and may die (Plant, 1956). Mo is the only micronutrient deficiency to occur on acid soils, and correction of pH prevents it for all crops except occasionally cauliflower. Leaf analysis preferred to soil analysis, but great analytical precision needed because critical concentration is only 0.1 mg Mo kg^{-1}.
Chloride	Essential element but for practical purpose it can be ignored.

Table 3. (continued).

Nutrient/mineral elements	Deficiency and toxicity symptoms - Predisposing factors
Toxicity	
Manganese	May occur as part of "soil acidity complex" (Wallace, 1961; Hewitt, 1983) if pH falls below 5.0. Brassica crops show inward rolling of leaf edges, interveinal chlorosis, and necrotic spotting. Lettuce older leaf edges become golden yellow. Mn concentrations above 500 mg kg^{-1} in the affected leaf margins would indicate the problem (MacNicol and Beckett, 1985). Bussler (1958) described the microscopic effects.
Aluminium	Whereas brassicas suffer Mn toxicity on acid soils, certain crops, notably sugar beet and celery are resistant to it, but instead suffer from aluminium toxicity, to which brassicas are tolerant (Hewitt, 1983). Symptoms are mainly on the roots - thickening, clubbing, and blackening, although celery shows petiole collapse and necrosis of the growing point.
Boron	This occurs mainly as a result of over-dosing when attempting to correct B deficiency (which is very easily done) and when irrigation water contains more than about 0.75 mg B l^{-1} (Lorenz and Maynard, 1988). Lettuce is rather susceptible: older leaves show pale margins.
Ammonia	Wilting, interveinal and marginal necrosis (scorch) of leaves; brown roots. Tissue NH_4^+ concentration is diagnostic but critical value is genotype-dependent (Barker, 1989). May occur in compost-grown plants following steam sterilisation, or storage of the compost (Bunt, 1976).
Chloride	May occur in saline conditions. Causes marginal leaf scorch similar to K deficiency.
Copper, Nickel, Zinc	See iron deficiency.

Plate No. 1.
Nitrogen deficiency in cauliflower: the right-hand row has received N: the plants in the left-hand row received no N: note the pigeon damage and pale colour on N_0 plants.

Plate No. 2.
Potassium deficiency in marrow (marginal leaf scorch).

Plate No. 3.
Magnesium deficiency in Brussels sprout (interveinal chlorosis).

Plate No. 4.
Boron deficiency ("cat-scratch") in marrow

Plate No. 5.
Tip-burn of lettuce, caused by localised Ca deficiency

Plate No. 6.
Marsh spot of peas, due to manganese deficiency

3.2.2. Determination of the nutritional status of plants

Plant analysis

The introduction of leaf analysis as a diagnostic technique is attributed to Lagatu and Maume (1924). Leaves (usually defined as those which are "youngest fully-expanded") are sampled from at least 25 randomly-scattered plants in the crop, preferably at a definable growth stage. For the immobile elements calcium, copper and sulphur, young leaves should be sampled. For details of sample preparation, see Bould (1983). After analysis, interpretation depends on the "critical concentration".

The classical "text-book" explanation of critical plant nutrient concentrations is as shown in Fig. 4. A pot or field experiment is done with increasing levels of the nutrient of interest, and the final yields are plotted against the concentrations of that nutrient measured in particular, carefully defined tissues analysed either at harvest, or at an earlier stage of growth (the latter is obviously more useful for diagnostic purposes). The critical concentration is defined as that corresponding to a final yield which is 95% (say) of the ceiling yield.

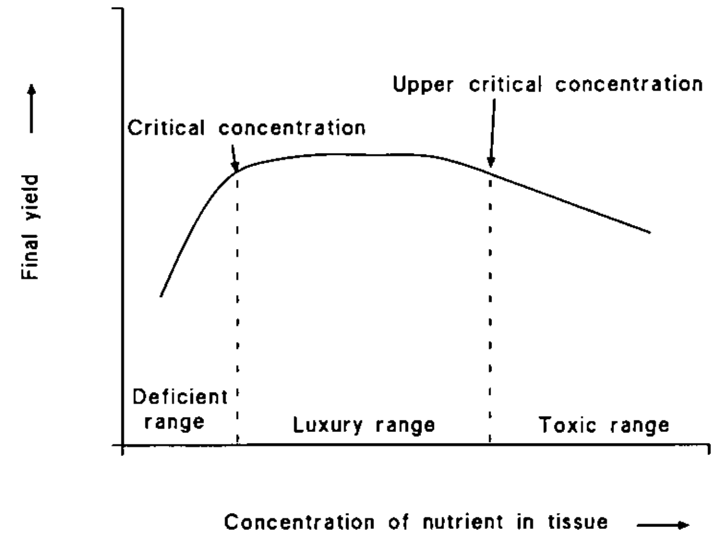

Fig. 4. Relationship between yield and nutrient concentration in tissue at an earlier stage of growth. The critical concentrations shown are for 95% of the maximum yield.

However, there is a great deal of variation in published critical concentrations for each species and element (Chapman, 1966; Reuter and Robinson, 1986) and in view of the possible changes in nutrient supply which might occur between leaf sampling and harvest, it seems likely that leaf analysis results should be used for "diagnosis" of current growth, rather than for "prognosis" for final yield (Scaife and Barnes, 1977).

Despite the above limitations, leaf analysis, if properly conducted, is the most reliable method of detecting nutrient deficiencies. The critical concentrations given in Table 2 are applicable to the "youngest fully expanded leaves" of semi-mature plants of most species, but the reader is referred to Reuter and Robinson (1986) for information on individual species. Clearly, values which are well above or below the critical value will give the most reliable diagnosis.

Tissue and sap tests

The concentrations given in Table 2 are for the total amount of each element in dry tissue, measured by any laboratory method which gives near 100% recovery. However, some nutrients are present in the plant in several forms, notably as "raw materials" which are not yet assimilated (e.g. nitrate, sulphate, inorganic phosphate). The concentration of these ions varies much more than those of the assimilated, organic forms, in response to changes in the balance of supply and demand (Peck *et al.*, 1974) and can thus be measured by much simpler, cruder techniques than are employed in laboratories. In the 1930s these "tissue tests" or "sap tests" were already in use in the USA (Carolus, 1936). In 1976, the firm E. Merck, of Darmstadt, FRG, introduced nitrate test strips into UK, and these were found to be useful for measuring the nitrate concentration in vegetable petiole sap (Scaife and Bray, 1977; BDH, 1984). In view of the great difficulties in optimising crop nitrogen nutrition, several authors have since used these strips and attempted to establish critical sap nitrate concentrations for various crops. However, there has been rather little take-up of these techniques, and the reason is no doubt because of the difficulties posed by apparent variation in the critical concentration due to light intensity, age of plant, etc. For example, Schrage (1990) showed that the sap nitrate concentration of lettuce varied by as much as three-fold during five days, whilst the soil nitrate hardly changed.

Nevertheless, the strips are useful for distinguishing between possible causes of chlorosis, and if users and experimenters were willing to take readings at dawn it might lead to greater reliability.

Diagnostic sprays

If a nutrient deficiency is suspected, individual elements (such as copper in the ADAS method mentioned above) or a "trace element cocktail" may be sprayed onto the crop in patches, or better, long strips. If symptoms disappear, or at least are absent in the new growth on the treated patches, but not on the rest of the crop, this is the most certain diagnosis possible. It may be too late to prevent yield loss in the current crop, but it should at least confirm or disprove other methods of diagnosis, which is useful for future crops. Even if no clear symptoms are apparent, it may be worth trying this method on a slow-growing crop, which may be in the "hidden hunger" zone. To establish a meaningful yield difference between the treated and untreated areas in the absence of any visible effect, however, would require the use of rigorous statistical methods.

3.3. Soil analysis

Soil analysis has the obvious advantage over plant analysis that it can be done before basal fertilizer is applied, and hence used to adjust the base dressing. Unlike plant analysis, where the total amount of each nutrient element is usually extracted from the leaf (except as mentioned above), soil analysis aims to imitate the plant by extracting only that fraction of the element which is available to the crop. Having chosen a promising extractant, the researcher has to show that the results correlate well with crop response. This was done for phosphorus by Van der Paauw (1971) who used water as an extractant. Different extractants will remove quite different amounts of nutrients from soils, so the grower or adviser must realise that it is essential to check that the analytical method used is the same as the one used to establish the criteria he is using to interpret the figures. Another precaution is to ensure that the soil sample is truly representative of the field: it should be made up of at least twenty subsamples, normally taken with an auger to plough depth over the whole field. Special methods have been developed for nitrogen, as will be discussed later.

4. How much to apply, when, how, and in what form?

4.1. Nitrogen

4.1.1. Estimating application rates

The optimisation of fertilizer nitrogen use has absorbed the attention of very many agronomists and others for at least a century.

Fig. 3 illustrates the extraordinary profitability of applying N to a high-value crop such as cauliflower. If one knew exactly where the optimum lay, there would be no problem, but because of the numerous transformations of N in the soil, the effect of weather on these and on crop growth and hence N demand, no system yet devised seems able to predict this optimum dressing with an accuracy (i.e. a coefficient of determination, R^2, between prediction and observation) much better than 30%. In the past, growers tended to "err on the high side" with N applications to avoid the risk of yield loss, but they are now under pressure from all quarters not to do this, because it leads to excessive nitrate in the produce and in the soil at harvest. This latter eventually pollutes water sources, and the cost of removing nitrate from water is about US\$ 15 (kg N)$^{-1}$ (Burns, personal communication).

The "Nitrogen Cycle" in soil (Fig. 5) is described in detail elsewhere (e.g. Mengel and Kirkby, 1987). Nitrogen in crop residues, organic manures, and the "old" organic matter in soil, is primarily in organic form (e.g. protein) and as such it cannot be taken up by plants. It must be mineralised by bacterial action, first to ammonia, then via nitrite to nitrate, in which form the great majority of uptake occurs. Only some 2-3% of "old" organic matter is mineralised each year, whereas vegetable crop residues are entirely mineralised in any time from 10 d to a few months depending on species and the temperature, moisture, and aeration status of the soil (Schrage, 1990).

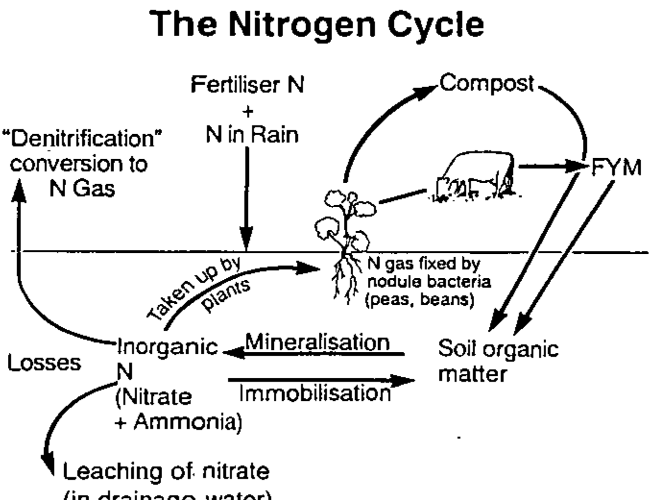

Fig. 5. The nitrogen cycle.

These large quantities of rapidly-mineralisable residues are, from the nutritional point of view, the most significant feature of vegetable cropping (Table 4). In a survey of 132 farms in lower Saxony in spring 1977, Böhmer (1980) found an average amount of soil mineral N (0-100 cm) of 78 kg/ha after cereals, 185 after 1 year of vegetables, and 316 kg/ha after several years of vegetable cropping.

Table 4. Fresh weight and nitrogen content of vegetable crop residues (after Schrage, 1990).

Crop	Fresh weight, t/ha	% N in fresh wt	kg N/ha
Cabbage	65	0.30	195
Cauliflower	55	0.36	198
Broccoli	66	0.32	211
Kohlrabi	15	0.32	48
Lettuce	15	0.36	54
Leek	25	0.35	88
Spinach	10	0.45	45

Once in the form of nitrate, the N can be leached through the soil profile. For non-cracking soils, the rate of leaching through a soil layer can be fairly well estimated by assuming that the water percolating through the layer mixes thoroughly with that already in the layer: once field capacity is exceeded, part of the water "overflows" to the next layer, taking with it a corresponding proportion of the nitrate (Burns, 1974). Needless to say, leaching is most severe when precipitation exceeds evapotranspiration, and when there little or no crop cover, as in a European winter, or in the humid tropics. Other processes which may occur are denitrification, ammonia volatilization (Terman, 1979), and ammonium fixation. The first is again a microbial process, in which nitrate is converted via nitrous oxide to nitrogen gas, rendering it useless to plants. It is promoted by anaerobic conditions, high temperatures, and high nitrate concentrations.

Ammonium-N, whether applied as fertilizer or occurring as an intermediate in mineralisation, can be lost if soil pH is above 7.2 (Barker, 1980). Ammonium fixation is a form of cation adsorption which may "lock up" ammonium nitrogen in large quantities if 2:1 lattice clay minerals are present.

Unlike most nutrient elements, therefore, nitrate nitrogen in the soil is only "buffered" in the sense that it may revert from the inorganic (mineral) form to the organic form under certain circumstances. So excess nitrate not only accumulates in the crop (see Fig. 6), but is leached out of the soil in winter. It may also damage the current crop in various ways.

It is little wonder that so many attempts have been made to find ways of optimising nitrogen dressings, and some of these will now be described.

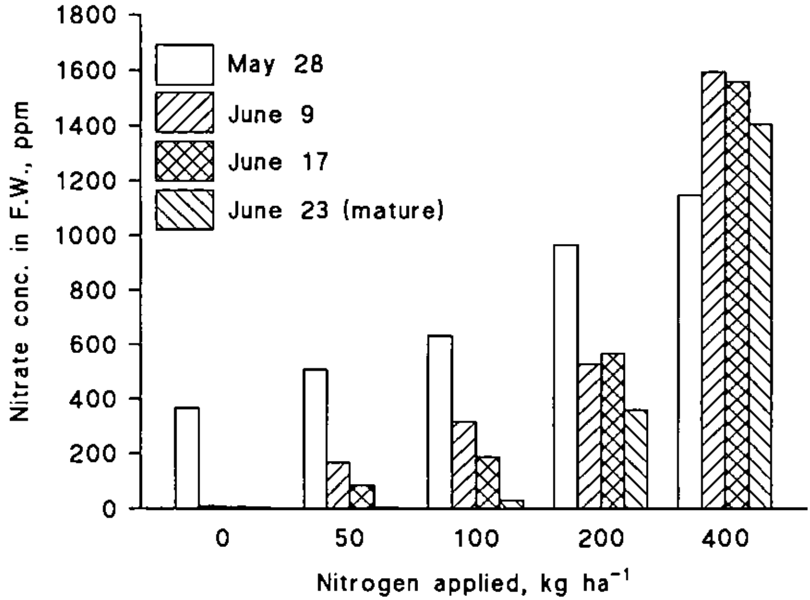

Fig. 6. Nitrate concentration in spinach leaves at 4 sampling dates with 5 levels of applied N (applied as ammonium nitrate) (Scaife, unpublished data). Such a pattern is typical of all crops (although actual concentrations differ from crop to crop - see Scharpf, 1991) and reflect a similar pattern of nitrate variation in the rooting zone of the soil.

ADAS (UK Agricultural Development and Advisory Service) method

This involves categorising fields (0, 1, 2) according to the previous crop grown, and adjusting N recommendations accordingly (MAFF, 1994). Index 0 thus represents a "low N residue" situation (e.g. cereals, sugar beet, poor pasture) needing more N fertilizer than index 2 "high residues" (e.g. liberal FYM, long high-N leys, lucerne). Index 1 is intermediate. The adjustments are usually about 50 kg N ha^{-1} for a unit change in the index, but they vary with crop and soil type.

The German "N_{min}" system

This is based on work carried out by Wehrmann and his colleagues and students at Hanover University since the 1970s (Scharpf, 1991). The essence of the method is that a soil sample is taken before applying the basal N dressing, to the depth expected to be exploited eventually by the crop (0-30, 0-60, or 0-90 cm), and analysed for mineral N ($NO_3N + NH_4N$). The total N requirement (initial soil N_{min} plus optimum fertilizer, kg ha^{-1}) is termed the "Sollwert" (Target value). The N fertilizer requirement is calculated by substracting the mineral N originally present in the soil from the Sollwert. Scharpf (1991) also gives tables of rooting depth for each species, allowances for freshly incorporated crop residues, etc.

The "KNS" system

This is a development of the N_{min} system, described by Scharpf (1991); and Lorenz *et al.* (1989). Unlike the original N_{min} system, it takes account of the N mineralised during the growth of the crop. In its present form, it involves soil sampling at least twice for N_{min} determination. The first sampling is made to 30 cm depth prior to basal N application, and enough extra N is given to take the crop to the top-dressing stage. A second sampling is then made to the full crop rooting depth, and this time the amount found is "topped up" to the amount needed to carry the crop to maturity. Target values are provided for both stages. In the Pfalz district of the Rhineland, the cost to the grower was subsidised until 1994 and there is a very quick turnround time for the soil analysis. The system is being recommended in the Netherlands for gherkins, fennel, leek, and lettuce (Soorsma, 1992).

Possible modifications to the KNS method

Soil sampling to these depths is arduous, and on some soils, quite impractical. It can be argued that the first sampling in the KNS system is unnecessary, provided that enough N is added to ensure the supply until the top-dressing stage (the desirability of splitting N dressings has already been mentioned). Since that stage should be at the beginning of the "grand period of growth" (to permit the passage of the machinery without damage to the crop) it follows that the total amount of N needed before then is very little. However, it is frequently observed in fertilizer experiments with broadcast basal N that an optimum level of about 100 kg N ha^{-1} is apparent when the plants are far too small to have used this amount (e.g. Scaife and Turner, 1984).This suggests that they are responding to the concentration of mineral

N in the root zone, and that if this concentration could be achieved by "banding" or placing the N close to the plants, less would be needed at this stage. Such techniques are used for maize in the USA, where a "Pre-sidedress soil nitrate test" (PSNT) is being tried. The advantage of this approach is that the soil test measures mineral N after previous crop residues, organic manures, etc., have had an opportunity to mineralise, and after the main leaching danger is past. Furthermore, it should be easier to estimate yield potential at this stage than before planting. This idea was also suggested by Scharpf and Weier (1988) and N_{min} sampling before top-dressing is being practised in Denmark (Sorensen, personal communication).

Simulation models and Expert Systems

By the use of simulation models, it is hoped to avoid soil sampling altogether. Such models ought to improve on tabular approaches to the problem because they take account of the timing of events. For example, cauliflower residues might be in organic form, and hence immune to leaching, one day, and almost entirely as nitrate, and thus susceptible to leaching, 10 days later. "User-friendly" versions of these models are now being developed, which the grower can use as a day-by-day management tool.

Expert systems are computer programs which provide advice based on numerous relevant factors, whilst not attempting to calculate growth, etc., on a daily basis (Fink and Scharpf, 1993).

Sap testing

Sap nitrate testing as a guide to N top-dressing has been tried (Scaife and Turner, 1987) but with disappointing results. There is no doubt that sap nitrate concentration is a sensitive indicator of the N supply/demand situation, nor that the commercially-available test strips are adequate for use on the farm. The problem has been to establish reliable critical concentrations for each growth stage. Some authors (e.g. Nitsch and Varis, 1991) appear to have had success with them.

The "Düngefenster"

This is a German word meaning "fertilizer window" and refers to the notion of leaving small marked patches of a crop with somewhat less nitrogen than the rest of the crop. The idea is that as the crop "runs out" of the nutrient, these patches will be the first to show deficiency symptoms, and therefore provide early warning of the need for a top-dressing.

It was tested on numerous vegetable species for nitrogen top-dressings by Schrage (1990) who found that in most cases, the indication of deficiency came too late to permit top-dressing with conventional machinery, and yields were therefore lower than with the "N_{min}" system.

Conclusions regarding N prediction methods

Although most of these methods would appear to be eminently sensible, they should be tested in extensive, preferably on-farm, field experiments to prove that they really work. When this has been done the results have often been far from satisfactory. For example, Neeteson (1985) showed that for 77 potato experiments on clay and loam soils in the Netherlands, the N_{min} method was no better, as regards profit, than if a fixed recommendation of 245 kg N ha^{-1} had been used on all sites. It did however result in an average reduction of 40 kg N ha^{-1} in the amount of N fertilizer needed. In view of the importance of nitrogen optimisation, it is vital to know whether these systems do work, and if not, why not. Some possible reasons why they might not are:

- Failure to locate the true optimum in the fertilizer experiments,
- N_{min} sampling coincided with a short period of immobilisation,
- Actual crop yield, and hence N demand, were not as expected,
- Mineralisation between sampling and peak demand was not as estimated,
- Errors in N_{min} analysis, or changes occurring between sampling and analysis.

There is little doubt of the value of N_{min} measurements when very high or very low values are found. Intermediate values are less useful.

Soil nitrate can be measured quite satisfactorily on the farm using Merckoquant test strips and a reflectometer (Nitsch, 1984).

4.1.2. Choice of N-fertilizer

Materials available

Types of N-fertilizers which are used in vegetable growing and their N percentage are listed below.

Ammonium fertilizers:

- Ammonia (80% N), ammonium sulphate (21% N).

Nitrate fertilizers:

- Calcium nitrate (16% N), sodium nitrate (16% N).

Ammonium nitrate fertilizers:
- Ammonium nitrate (about 34% N), calcium ammonium nitrate, which is a mixture of ammonium nitrate and calcium carbonate (21-27% N), ammonium sulphate nitrate (26-30% N).

Amide fertilizers:
- Urea (45-46% N), calcium cyanamide (20% N).

Solutions containing more than one form of N:
- Urea ammonium nitrate solution (28-32% N).

Archer (1988) gives more information about these materials.

Ammonium sulphate has an acidifying effect on the soil and may be useful on alkaline soils, or where sulphur is needed. Urea should not be used on such soils, since large quantities of N may be volatilized as ammonia (Fenn and Miyamoto, 1981). Calcium nitrate, particularly when used as a foliar spray, has been shown to control various calcium-related vegetable disorders (Maynard, undated). Calcium cyanamide ("Kalkstickstoff") may limit the damage to Brassica crops caused by clubroot (*Plasmodiophora brassicae*) (Mattusch, 1978). Other things being equal, the choice of N source is governed by cost and convenience.

Nitrate versus ammonium

Apart from urea, these materials contain varying proportions of ammonium and nitrate nitrogen. Unless nitrification inhibitors (see below) are used, ammonium is converted by soil bacteria to nitrate very quickly at neutral pH and favourable temperatures, so that most crops obtain most of their nitrogen as nitrate.

Barker and Mills (1980) reviewed the pros and cons of nitrate and ammonium use. Ammonium is absorbed onto the soil cation exchange surfaces and cannot be leached, but it can be toxic (as when ammonia gas is evolved under alkaline conditions), or can compete with other cations such as potassium and calcium, possibly causing physiological disorders, such as tipburn of Chinese cabbage (AVRDC, 1985). Although some authors have shown that a small proportion of ammonium-N can enhance yields of certain crops (Ikeda, 1988), Barker concludes that the inclusion of ammonium in the fertilizer needs to be carefully regulated. The presence of a certain amount of nitrate can reduce the toxic effects of ammonia.

Slow release N-fertilizers

To reduce the risk of leaching and salt damage, various "slow-release" or "controlled release" nitrogen fertilizers have been developed over the years, including Nitroform, or Ureaform (Urea-formaldehyde), "Gold-N" (sulphur-coated urea), "Osmocote" (resin-coated NPKMg + trace el. compounds), "Ficote" (polymer-coated compounds), etc. Some of these products are in regular use for nursery stock etc., but for field-grown crops they are generally too expensive, and indeed may be too slow for quick-maturing crops (Lorenz *et al.*, 1972; Kolota, 1984). Controlled-release N sources and nitrification inhibitors were reviewed by Prasad *et al.* (1971) and Maynard and Lorenz (1979).

Nitrification inhibitors

Several materials such as nitrapyrin (N-serve), and dicyandiamide (Didin or DCD) have been found to inhibit nitrification (Prasad *et al.*, 1971), thus keeping the N in the ammonium form, and reducing the leaching risk. This risk is probably minimised more cheaply by using a split dressing of normal N fertilizer such as ammonium nitrate (AN) (Kolota, 1984). There has also been interest in inhibitors to reduce the nitrate concentration in vegetables at harvest time, which it may do (e.g. Venter, 1984), but the question arises as to whether the residues of the inhibitor in the crop are any less harmful to the consumer than the nitrate. According to Maynard and Lorenz (1979), nitrapyrin has low mammalian toxicity and is not taken up by plants.

Aqueous ammonia, anhydrous ammonia and "ammonium-depots"

Aqueous and anhydrous ammonia appeared in the USA in the forties and their use in the UK increased rapidly in the sixties (Page, 1972) although it was then only 1% of UK N use compared with 35% in USA and 18% in Denmark. The raw material is cheap, but to avoid gaseous losses it must be injected into the soil using special equipment, which is normally done by contractors. Page *et al.* (1974) found that both forms were as effective as ammonium nitrate for Brussel sprouts.

The "ammonium-depot" system was developed by Sommer (1991). Localised zones of aqueous ammonia, with a DCD inhibitor, are placed near the crop roots, which proliferate around them. The author reports 24 experiments with six vegetable species in which the depot system is compared with calcium ammonium sulphate in split dressings. He found no reduction in yield or quality, and a reduction in crop nitrate levels at harvest.

4.1.3. Methods of applying nitrogen

Single broadcast base dressing

All or much of the N for vegetable crops is often applied broadcast onto the soil shortly before drilling or planting the crop, either as a "straight" N fertilizer, such as ammonium nitrate (AN), or as a compound containing P, K, etc. This is a cheap and simple approach, and has the advantage that with moderate rainfall, the N should be fairly well spread through the rooting zone by the time it is needed. If part of the N is in the form of ammonium (e.g. 50% in AN), this part is protected against leaching for a few weeks, depending on soil temperature. "Spinners" or pneumatic full-width distributors are used to broadcast the material, preferably just before seedbed preparation.

Split dressings

Many growers split their nitrogen dressings into a basal application and one or more top-dressings (= side-dressings). Although there are reports (Everaats, 1993) which lend little support to this practice, there is every reason to believe that it is sensible, because we know, for example, that basal N dressings of 100 kg N ha^{-1} or even less can be harmful, particularly to drilled crops in dry conditions (Page and Cleaver, 1983). On the other hand, one cannot omit the basal N dressing, because in moist seedbed conditions the optimum N rate may be quite high (Greenwood *et al.*, 1989). There seems to be little justification for more than one top-dressing, and the best time for this is at the beginning of the "grand period of growth" which is roughly when broad-leaved plants are about 10 cm across. At that time it is still possible to get into the crop with machinery, and there is very little danger of further leaching. A 50:50 split (base:top-dressing) is normally appropriate. Unless rain is expected, top-dressing should be followed by irrigation to wash it into the soil and minimize leaf scorch. Late top-dressing should be avoided as it increases the nitrate content of the crop.

Starter fertilizers, placement and banding

Seeds contain a limited reserve of nutrients which is sufficient for only 7-10 days' growth (Hole and Scaife, 1993). It is therefore essential to provide a favourable nutrient environment around the germinating seed. Costigan (1988) has shown that broadcasting may sometimes fail in this respect, and has reviewed the work done on placement at the National Vegetable Research Station, UK (now HRI, Wellesbourne) prior to 1988.

Fertilizer placement has been much used in the USA, especially for P and K fertilizers (Randall and Hoeft, 1988) but much less so in Europe. Cooke *et al.* (1956) described UK experiments with 8 vegetable species, most of which benefitted greatly from placement of PK and NPK. Recent work with onions and lettuce (Stone and Rowse, 1992) showed benefits of injecting 20 kg N ha^{-1} as a solution of diammonium and monoammonium phosphate below the seeds, even when ample N, P and K had been broadcast (Plates 7 and 8). Lettuce yields were increased from 5 t ha^{-1} on the control plots to 23 t ha^{-1} on the plots with 20 kg N ha^{-1} as starter fertilizer, representing an uptake efficiency of about 200%. (This might of course be due to the accompanying P, but the "priming" effect of N fertilizer is a known phenomenon; Jenkinson *et al.*, 1985).

Plate No. 7.
Stanhay drill unit modified to place liquid fertilizer 25 mm below the seed. The solution (10-20 ml m^{-1} row) is forced by a land-wheel-driven peristaltic pump down a tube attached to the trailing edge of the tine on the left. The soil is compressed by the press wheel before the seed is drilled.

Plate No. 8.
Effect of starter fertilizer on onions at the salad stage on a sandy loam soil of high PK status: A. no fertilizer. B. starter solution providing 20 kg N ha^{-1} and 60 kg P_2O_5 ha^{-1}. C. N broadcast as ammonium nitrate at 20 kg N ha^{-1}. D. as C, but 160 kg N ha^{-1}. The final harvest of 48 t ha^{-1} of bulbs was achieved with 90 kg N ha^{-1} (including 20 as starter), compared with 180 kg N ha^{-1} broadcast.

Other species, however, are less responsive (Stone, personal communication). Plants fed with ammonium N tend to acidify the rhizosphere, and this helps to keep the accompanying P in solution. Nitrate uptake generally results in an increase in rhizosphere pH (Marschner, 1986).

Starter fertilizer can be used to satisfy the NPK needs of the crop for the first month or so of life for drilled crops. There would appear to be considerable scope for combining the technique with the "KNS" or "PSNT" systems to minimise N use.

Foliar feeding

The problem with top-dressed N is that there may not be sufficient rainfall to wash it into the soil. Foliar application of fertilizers is thought to avoid this problem, but Gooding and Davies (1992) considered that for foliar urea sprays on cereals, this question is still open. These authors state that the danger of leaf scorch is less with urea than with other forms of N-fertilizers. Although 15 kg N ha^{-1} is a figure often quoted as an appropriate amount to apply as foliar urea, Burghardt and Ellering (1986) applied 100 kg N ha^{-1} as an NPK compound to the foliage of seven vegetable crops, increasing yields by 12-74% without leaf damage.

4.2. Phosphorus

4.2.1. Application philosophy for P and K

There are two possible approaches to P (and K) fertilization. The first is to "fertilize for the crop" which means applying the amount which, on the basis of a soil analysis and the known response characteristics of the crop about to be grown, will be optimal for profit. The other it to "fertilize for the soil", i.e. to apply a "maintenance dressing" of P, not necessarily every year, to keep the soil P concentration at a level which is known to satisfy the requirements of all the crops in the rotation. This is done by replacing the P removed by the crops, which, as we have seen, may be very much less than the broadcast dressing giving maximum yield on a low-P soil. The second approach is possible, because, unlike mineral N, P is strongly held in the soil (both by anion exchange and in sparingly soluble forms) and is not significantly leached out (from mineral soils) in the winter.

Although the national figures for P and K in Table 8 would imply that "fertilizing for the crop" is officially encouraged, most of my correspondents were in favour of the "maintenance" approach, which is obviously the more convenient (Scharpf, Gysi, Sorensen, personal communication). Scharpf (for Germany) considers that a suitable long-term annual average for vegetable farms is 60 kg P_2O_5 ha^{-1}, which is in close agreement with the mean P removal of 15 species in the UK listed by Greenwood (1974a) of 55 kg ha^{-1}. Gysi (for Switzerland) says that average P application should equal the export, and is currently too much. The figure given by him (Gysi, 1993) for the amount exported in 1990 from a 19 hectare mixed vegetable farm was 49 kg P_2O_5 ha^{-1}. Sorensen recommends 70-90 kg P_2O_5 ha^{-1} for vegetables grown in Denmark on soils of medium P status.

In the past, vegetable growers in the UK and elsewhere in Europe have added more P than was removed, and soil P indices have risen to very high levels as a consequence. By maintaining these high levels, they may hope to avoid the risk of P deficiency even in highly responsive crops such as spinach and lettuce. Costigan (1985) has shown that this may not be so, because these crops require a very high soil solution P concentration soon after emergence. Alt (1984) summarised the results of 24 P/K/Mg experiments with twelve species grown over 15 years at Osnabrück, and showed that the average optimum level of P_2O_5 was 104 kg ha^{-1}, whereas the amount removed in the edible parts was only 44 kg ha^{-1}. This might explain why growers add more than is removed, and lends support to the use of P-containing starter fertilizers, which satisfy plant demand with minimal quantities of P. The question is whether there any disadvantage, either for the grower or for the environment, in maintaining a very high soil P status. According to Mengel and Kirkby (1987), very little P is leached from mineral soils, but there is a danger that on certain soil types P will be "fixed" i.e. rendered unavailable by conversion to insoluble forms such as apatite. P can be leached from peat soils and this is creating a eutrophication problem in the Florida Everglades (Espiñoza *et al.*, 1993). It is the element causing most eutrophication, and although the major source of P in rivers is of domestic and industrial original, surface soil runoff is undoubtedly also responsible (Sharpley and Menzel, 1987). On some soils the use of excessive P can run the risk of inducing zinc deficiency (Mengel and Kirkby, 1987).

4.2.2. Phosphorus fertilizers

The materials most used, and their P_2O_5 percentages are:

Water-soluble types (quick-acting):
- single superphosphate (18-20% P_2O_5 + 11-14% S);
- triple superphosphate (45% P_2O_5).
- ammonium phosphates:

* monoammonium phosphate (11% N, 52% P_2O_5)
* diammonium phosphate (18% N, 46% P_2O_5)
* ammonium polyphosphate (10-15% N, 35-62% P_2O_5).

Partly water-soluble types (quick- and slow-acting):
- partly acidulated phosphate (23-26% P_2O_5 at least one-third water-soluble).

Slow-acting types:
- dicalcium phosphate (citrate-soluble; 40% P_2O_5).

Very slow-acting types:
- rock phosphate (finely-powdered soft type, e.g. 30% P_2O_5), with reactivity indicated by formic acid-solubility; permitted minimum is about one-half of total P_2O_5 content).

Follett *et al.* (1981) and Archer (1988) give further details. The great majority of fertilizer P is applied as NPK compound fertilizers (which chemically are mixtures), in which triple superphosphate (monocalcium phosphate) is the main P-containing ingredient. The use of rock phosphate cannot be recommended for vegetable crops because of its low solubility (Khasawneh and Doll, 1978). The same applies to all other slow-acting forms. Single, or normal superphosphate contains sulphur (as gypsum) and is therefore valuable where this element may be deficient.

4.2.3. Methods of applying P

By now it should be clear that, if it is feasible, it is desirable to place P, preferably in company with some ammonium, e.g. as ammonium phosphate, near the young seedling. It this is not possible, the next best option would appear to be to apply the maintenance P dressings in large doses for the P responsive crops in the rotation, with none for the others.

4.3. Potassium

4.3.1. Amounts of K to apply

As with P, K is strongly adsorbed onto soil colloids and the response of individual species is not related to the amounts they take up (Greenwood *et al.*, 1974a). Thus, the same approach, that of applying "maintenance dressings" equal to offtake, is recommended in most countries. Scharpf (personal communication) suggests 200 kg K_2O ha^{-1} as an average annual dressing for German conditions with high yields: in Switzerland, Gysi's 19 ha farm showed an average annual removal of 141 kg K_2O ha^{-1}.

For a more precise calculation of the average annual dressing of K to apply, the reader should refer to Table 9, from which it is possible, by considering the proportion of different crop species in the rotation, and making appropriate adjustments for yields actually obtained, to arrive at an average annual K dressing which closely balances the K offtake.

However, the question arises with the maintenance approach "what level of soil K should I maintain?"; i.e. before settling down to a programme which replaces the K sold off in the crop, should one increase or decrease the soil K status by applying more or less than the "offtake" amounts for several years in order to establish a higher or lower soil K status than already exists? If very high levels are maintained, it is likely that crops will take up "luxury" amounts of K, as vegetables readily do, and this is wasteful. Furthermore, it will increase the risk of K leaching, as it can on light or peaty soils (Mengel and Kirkby, 1989). On the other hand, if very low soil K levels are maintained there is a possibility that the more responsive crops, such as spinach, (which apparently has a high K intensity requirement) might not achieve maximum yield when the maintenance dressing is applied.

Little is known about the K intensity requirements of different vegetable species, but the NPK predictor (NVRS, 1980) was intended to try to throw light on this problem by providing an estimate of the responsiveness of numerous vegetable species when grown on soils of varying N, P, or K status. It was based on the work of Greenwood *et al.* (1974a). Table 5 shows the predicted percentage of maximum yield (i.e. that obtainable with optimum K fertilizer) which 19 vegetable crops might be expected to give on soils at three levels of K status, when not given any K fertilizer. The crops are ranked in increasing order of responsiveness. If a rotation consists of crops near the top of the list, one can allow the soil K level to fall to as little as 60 mg K l^{-1} (measured by the ADAS method, using ammonium nitrate as extractant) whereas if it includes crops at the bottom of the list, soil K levels should exceed 150 mg l^{-1}. If responsive and non-responsive crops are to be grown in rotation, large amounts of K should be applied for the responsive crops, with less, or none, for the non-responsive ones, so that the average annual dressing balances the average annual offtake.

Table 5. Percentage of maximum yield expected from various vegetable species when grown on soils of different K status (derived from NVRS, 1980).

	Available* soil K		
	<60	60-150	>150
	------------------ mg l^{-1} ------------------		
Calabrese	100	100	100
Pea	98	98	100
Winter Cabbage	95	98	100
Swede (Rutabaga)	95	98	100
Summer Cabbage	95	98	100
Brussels Sprout	95	98	100
Lettuce	91	98	98
Red beet	87	98	98
Carrot	83	95	98
Parsnip	83	95	98
Broad bean	80	95	98
Leek	80	95	98
Potato	77	91	98
Dwarf bean	75	91	98
Onion	75	91	98
Radish	75	91	98
Cauliflower	72	87	95
Turnip	58	80	91
Spinach	34	53	75

* ADAS method K extracted by ammonium nitrate.

From the work of Alt (1984), it seems that the optimal dressing of K for most vegetable crops is much closer to the maintenance dressing than is the case for P, suggesting that there is no particular benefit to be expected from boosting K concentrations near the plants by means of placement.

4.3.2. Potassium-containing fertilizers

Apart from some low grade unrefined products, all substances used as potash fertilizers are high analysis products, water soluble and quick-acting. They can be grouped as:

Cl-containing potash fertilizer:

- potassium chloride or muriate of potash - MOP - (40-60% K_2O), the lower grades provide Na in addition to K_2O and with or without Mg.

Cl-free potash fertilizer:
- potassium sulphate - SOP - (50% K_2O; 18% S)
- potassium magnesium sulphate (30% K_2O, 18% S, 6% Mg).

4.3.3. The best potash fertilizer and methods of application

Chloride or sulphate of potash?

The main choice is between chloride and sulphate of potash. Zehler *et al.* (1981) summarised research comparing the two forms of potash fertilizers. According to them, SOP is to be preferred due to its advantageous side effects if:

- sulphur application is needed (low S-supply from the soil and high sulphur requirements of the vegetable crops as for instance, those belonging to the family Cruciferae);
- chloride-sensitive vegetables are grown, i.e. french beans, broad beans, onion and chillies;
- vegetables are grown which are chloride neutral but prefer sulphate, i.e. tomato, radish, kohlrabi, cauliflower, spinach and peas;
- soil salinity is a problem, because sulphate has a lower "salt index" per ion of K (Yadav and Tomar, 1990);
- very high rates of fertilizers are used as in intensive vegetable growing;
- quality parameters are favoured by sulphur (chap. 4.4.3.).

The majority of K is applied as compounds which are available in the chloride-containing and chloride-free form. The use of both potassium chloride (MOP) is common if no restrictions due to undesirable side effects of this type of K fertilizer are expected and the sulphur supply of the soil is abundant.

The sodium-containing sources are useful for those crops which respond to it (see 4.4.4.).

Methods of application

It is generally agreed that K fertilizers are best broadcast onto the soil and worked in before planting. This can be done in the autumn if necessary except on organic or sandy soils, through which some leaching can occur. Placement is not generally advisable: in particular potassium chloride can cause salt damage to germinating seedlings. If potassium is to be placed near the seeds, SOP should be used.

Top-dressing of K salts, particularly on clayey soils, is unlikely to be effective because of adsorption of K very near the soil surface.

Split application should only be considered if highly responsive vegetables are to be grown on soils low in available potassium and low sorption capacity.

4.4. Secondary nutrients

4.4.1. Calcium-related physiological disorders

There are several physiological disorders of vegetable crops which are thought to be due to a localised deficiency of calcium in the tissues. These are tipburn of lettuce (Collier and Tibbits, 1982) (see Plate 5) and cabbage, internal browning of Brussels sprouts (Maynard and Barker, 1972), and blackheart of celery (Geraldson, 1954) and chicory.

Each is a form of necrotic breakdown of young leaf tissue. Their severity is influenced by such factors as soil compaction, irregular irrigation, rapid growth, and cation antagonism. The last-named may be the chief cause in the case of tipburn of Chinese cabbage, which is now said to be a kind of ammonia toxicity (AVRDC, 1985). In the case of iceberg lettuce the practical solution in the UK has been the adoption of the tipburn resistant variety Salinas from the USA. Use of resistant varieties also seems to have largely eradicated internal browning of Brussels sprouts. In Florida, the disorders have been overcome by the use of high quality (i.e. low salinity) irrigation water, and appropriate nutritional practices (Locascio, 1987).

4.4.2. Magnesium deficiency

It is usually considered that there is very little "hidden hunger" zone for magnesium, which means that there is no need to worry about Mg deficiency unless symptoms are seen. These can be very striking in brassicas (Plate 3). The diagnosis should be confirmed by leaf analysis, and immediate treatment is possible by foliar sprays every two weeks of 2% Epsom salts ($MgSO_4.7H_2O$) at 500-1000 l ha^{-1} (a suitable wetting agent should always be included in foliar feeds). However, this should only be used as an emergency measure: for future crops either magnesian limestone (10% Mg), Kieserite (16% Mg; 23% S), Epsom salts (10% Mg) or other Mg-containing fertilizers should be incorporated into the soil, either at the rate recommended for the next crop, or as a "maintenance dressing" of 15-20 kg ha^{-1} $year^{-1}$.

4.4.3. Sulphur

Certain vegetable crops, notably crucifers, have a high sulphur requirement, and since atmospheric levels of sulphur dioxide have been falling, we are beginning to see cases of sulphur deficiency in these and other crops. Apart from its effect on yield, sulphur is an important contributor to flavour in brassicas (Freeman and Mossadeghi, 1972) and pungency in alliums (Freeman and Mossadeghi, 1970). Growers, particularly of these crops who farm well away from industrial centres, would be well advised to carry out periodical leaf samplings, and if S concentrations fall below 0.35% (in d.m. of young leaves) they should use sulphur-containing fertilizers, such as single superphosphate or sulphate of potash. The concentration of sulphate-S in rainfall varies from 0.5 to 4 mg S l^{-1} depending on the distance from industrial centres (Zehler *et al.*, 1981).

4.4.4. Sodium

It is doubtful whether sodium is essential for any higher plants, but sodium can beneficially replace part of the potassium for crops of the family Chenopodiacae (beets); also turnips, celery, and carrots (Archer, 1988). In the UK, ADAS recommends the use of 150 kg Na ha^{-1} for carrots, and a reduction of 60 kg ha^{-1} in the K_2O dressing on light soils: for celery, on all soils except fen peats and silts, the same amount is recommended without reduction in the K application. The salt must be ploughed in at least a month before sowing. There are also reports of sodium improving the flavour of root crops e.g. swedes (Truog *et al.*, 1953). Na may be applied either as sodium chloride, as Chilean potash nitrate (9-18% Na), Kainit (9-18% Na), Sylvinit (25-28% Na) or sodium nitrate (26% Na). A sufficient amount may also be present in irrigation water, and in rain (especially near coasts).

4.5. Micronutrients (trace elements)

Vegetable growers are often familiar with one or two micronutrient disorders (e.g. manganese deficiency in Eastern England), but they are easily persuaded that there may be others present in a symptomless form, which may be reducing yield or quality. The cost of applying a "cocktail" spray, containing several micronutrients, is seen as a cheap insurance against this risk.

To such growers the best advice would seem to be:

- Have a complete leaf analysis done: if the results are well above the critical values (Table 2), and the crop looks healthy, a response is most unlikely,

- If you do decide to spray, leave two or three clearly marked untreated strips for comparison.

Certain vegetable growing areas are subject to numerous micronutrient deficiencies: such a one is Florida. The history of the discovery and correction of these problems has been related by Locascio (1987) and Locascio and Fiskell (1987).

If particular deficiencies or toxicities are diagnosed (see Table 3), the following treatments are recommended:

- Iron (most unlikely): if induced by other heavy metals (e.g. from slurry), spray crop with .05% Fe EDTA at 500-1000 l ha^{-1}.
- Manganese: spray with manganous sulphate at 10 kg ha^{-1} in 500 l of water every two weeks. Soil Mn application is not considered effective in the UK, because Mn is precipitated at high pH. On Florida histosols, Mn included in broadcast fertilizer is effective if pH is below 6.5: above this pH, band placement of Mn below the drill is effective (Sanchez *et al.*, 1989).
- Zinc deficiency: apply zinc sulphate ($ZnSO_4.7H_2O$). at 5 kg ha^{-1} as a high volume foliar spray. See "Zinc in Crop Nutrition (undated)" for further details.
- Copper deficiency: apply copper sulphate ($CuSO_4.5H_2O$) to soil at 60 kg ha^{-1}. Such a dressing should last for 10 years. See Shorrocks and Alloway (undated) for details.
- Boron deficiency: foliar spraying with "Solubor" at 10 kg ha^{-1} is possible but usually too late if symptoms already present: otherwise use a boronated fertilizer or apply Solubor or borax to soil to supply 2 kg B ha^{-1} during seedbed preparation. See Shorrocks (undated).
- Molybdenum deficiency: for cauliflowers only: drench transplants with a 0.03% solution of sodium or ammonium molybdate before planting out. Seed treatment with 35 g of sodium or ammonium molybdate ha^{-1} is also feasible. Maintain correct soil pH.
- Manganese and aluminium toxicity: do not allow soil pH to fall below 6 (5.5. for peat soils).

4.6. Soil pH adjustment

Soils should never be limed without carrying out a pH measurement, or better, a proper lime requirement measurement on each field to be limed, or even on separate parts of fields. A lime requirement test takes into account not only the pH, but the amount of lime needed to bring about a change of one pH unit, which differs with the clay and organic matter content of the soil. For mineral soils the aim should be to keep the pH near to 6.5: for peat soils, 5.8 (Archer, 1988). If this is done, there will be a satisfactory supply of Ca to the roots, but this does not ensure the absence of physiological disorders (see 4.4.1.). Above pH 7 there is an increasing risk of trace element deficiencies. The acceptable pH range for most vegetable species is 5.5-7.0. For peas, broad and French beans, celery and lettuce, it should not be below 6: cabbage, chicory, mustard, parsnip, swede and turnip can tolerate values just below 5.5 (MAFF, 1994). If clubroot is present, pH for brassicas must be above 7. All these values refer to water extraction: if $CaCl_2$ extraction is used, pH values will be about 0.5 units lower. Table 6 shows the amounts of ground limestone needed to adjust the pH of different soil types. It takes several months for liming to thoroughly correct the pH: much longer on very acid soils or with coarsely ground liming materials.

Table 6. Limestone (t ha^{-1}) needed to change the soil reaction of the plough layer (adapted from Lorenz and Maynard, 1988).

Change in pH needed*	Sand	Sandy loam	Loam	Silt loam	Clay loam	Peat (muck)
4.0-6.5	2.9	5.6	7.8	9.4	11	14
4.5-6.5	2.5	4.7	6.5	7.8	9.4	11
5.0-6.5	2.0	3.8	5.2	6.3	7.4	7
5.5-6.5	1.3	2.9	3.8	4.5	5.2	3
6.0-6.5	0.7	1.6	2.0	2.5	2.7	0

* For peat soils, the target pH is 5.8.

N.B. If burned lime, hydrated lime, or dolomitic limestone are used, the amounts required will be 64%, 82%, or 86% respectively of the amounts shown here.

Large pH adjustments with high amounts of lime have to be avoided. A step-by-step approach is recommended.

Soil pH can be reduced by the use of elemental sulphur. The quantity needed to lower pH from 7.5 to 6.5 varies from 500 kg ha^{-1} on sands to 1000 kg ha^{-1} on clays (Lorenz and Maynard, 1988). Sulphur has also been band-placed to reduce pH locally below the seed (Sanchez *et al.*, 1989).

On many soils, especially tropical oxisols, aluminium toxicity, and the effect of soil aluminium on P uptake, are critical factors governing liming practice. These questions have been discussed in detail by Haynes (1984).

The materials used for liming are ground or screened limestone or magnesian limestone, ground or screened chalk, sugar beet or waterworks lime sludge, and burnt or hydrated lime. The neutralising value of these materials varies from about 20% of that of pure CaO for the sludges, to 80-95% for burnt lime (see Archer, 1988, for more details).

5. The organic approach

So far, nothing has been said about organic materials or organic farming methods. A feature of vegetable farming is that it produces large quantities of very valuable crop residues.

On commercial farms, they are usually ploughed in where they grew. It seems to have been only recently realised that the "softer" of these residues are decomposed within a very few weeks at summer soil temperatures (Schrage, 1990) and their N, P and K content (roughly 3, 0.3 and 2% of their dry weight) should be available to the following crop, unless winter intervenes in which case much of the N may be lost by leaching.

Bulky organic manures, in which we will include cattle and pig slurry and sewage sludge, must be returned to the land in the most effective way, and their nutrient content allowed for. These contents are shown in Table 7. For P and K, one can calculate the amounts being returned from this table and count these towards the "maintenance" amount of roughly 60 kg P_2O_5 ha^{-1} and 200 kg K_2O ha^{-1} already mentioned as typical offtakes in intensive vegetable production. For nitrogen, the position is more difficult because the rate of mineralization of these bulky materials is rather unpredictable. Typically, organically grown crops are likely to suffer from a deficiency of nitrogen in early growth (Keipert *et al.*, 1990) and a surfeit of it towards harvest. Hence it should not be imagined that such crops will necessarily be low in nitrate: the opposite sometimes happens.

The "biodynamic" method of organic fruit and vegetable production was compared with "conventional" production in large-scale trials from 1977-85 by Keipert *et al.* (1990). They found that the method was more expensive, more labour-demanding, lower-yielding, and more prone to failure than conventional methods. They stated that there were no significant differences in quality from the two methods.

Table 7. Typical nutrient content of animal manures (from MAFF, 1994).

	DM	Total nutrients			Available nutrients[1]		
	%	Nitrogen	Phosphate	Potassium	Nitrogen[4]	Phosphate	Potassium
Fresh FYM[2]			kg/t			kg/t	
Cattle	25	6.0	3.5	8.0	1.2	2.1	4.8
Pig	25	7.0	7.0	5.0	1.4	4.2	3.0
Poultry manures			kg/t			kg/t	
Layer manure	30	15	13	9.0	5	7.8	6.8
Broiler/turkey manure	60	29	25	18	10	15	14
Slurries			kg/m^3			kg/m^3	
Dairy[3]	6	3.0	1.2	3.5	1	0.60	3.2
Beef[3]	6	2.3	1.2	2.7	0.7	0.60	2.4
Pig[3]	6	5.0	3.0	3.0	2	1.5	2.7

Notes: [1] Nutrients that are available for utilization by the next crop.
[2] Values of nitrogen and potash will be lower for FYM stored in the open or for long periods.
[3] It is common for farm slurries to contain approximately 6% DM. Slurries of DM% other than 6% will have greater or lesser concentrations of nutrients than those shown above. Undiluted slurry will usually contain approximately 10% DM.
[4] This column refers to spring application. See the source reference for more details.

Vogtmann *et al.* (1992) compared the use of "biogenic waste compost" and farmyard manure compost, both supplemented or not with concentrated organic NPK fertilizers, with inorganic NPK materials for cabbage and carrots. Inorganic NPK (120-240 kg N ha^{-1} including N_{min}) gave the highest yields but also (in cabbage) much the highest crop nitrate concentrations. As regards post-harvest quality and sensory properties (not described) the control (no fertilizer) and other low-N treatments ranked highest.

6. Vegetable nutrition and crop quality

Nitrogen

Nitrogen is necessary to produce plants of suitable size for the market: without it, growth is slow and the produce may be tough.

High nitrogen supply normally lowers the sugar content of plants, and zero-N plants are sometimes noticeably sweeter than the others (Plate 1).

N top-dressings increased bitterness in Brussels sprouts (Scaife and Turner, 1985) which suggests an increase in the content of certain glucosinolates (Fenwick *et al.*, 1983). Fischer (1992) showed that, for kohlrabi, volatile flavour compounds were maximised by a low-N moderate-K regime. The bitter taste of purée from cooked beetroot grown with high nitrogen is due to pyrrolidone-carboxylic acid (PCA) derived from glutamine (Shallenberger and Moyer, 1958). According to Wedler (1985), high N reduces storability of carrots, cabbage and dwarf beans, and impairs the flavour of carrots, celery and cabbages. It increases the nitrate concentration in the produce (Maynard *et al.*, 1976), which has been suggested as a possible cause of stomach cancer (although the bulk of evidence would discount this view; Forman *et al.*, 1985); and is undesirable in baby food because of the danger of methaemoglobinaemia (Maynard *et al.*, 1976). Nitrate is an oxidising agent and can cause detinning of cans (Maynard *et al.*, 1976).

Excessive nitrogen is also implicated in several physiological disorders, such as hollow stem of cauliflower (Scaife and Wurr, 1990) and black midrib of stored cabbage (Berard, 1990). There is general agreement among growers that it leads to softer growth. It exacerbates splitting, forking and bolting of carrots (Batra and Kalloo, 1990).

The effects of nitrogen on vitamin content of vegetables are variable and small compared with the effects of other factors. High nitrogen usually depresses the ascorbic acid content (Sorensen, 1984), but other vitamin levels are sometimes increased (Miller *et al.*, 1956).

Rather little information about the effects of K on crop quality is available relating specifically to field vegetables. The subject was reviewed by Cummings and Wilcox (1968). They stated that most quality characteristics improved with increasing K over the same range as led to yield increase, and cited work showing that the amounts and proportions of organic acids, but not their actual chromatograms, are profoundly affected by K. They pointed out that the characteristic symptoms of K deficiency, namely marginal necrosis of leaves, may affect the quality of leafy vegetables; however, this would apply only in cases of fairly extreme deficiency. In general, K is known to be important for turgor and the strength of stems, etc.

In the same book, Lucas (1968) drew attention to the adverse effects of excessive K in increasing the incidence of calcium-related physiological disorders, such as blackheart, brown checking, and magnesium chlorosis of celery, and internal tipburn of cabbage. On the other hand, Peck and Stamer (1970) reported a reduced incidence of internal black tissue in late cabbage with increasing K application. There is considerable evidence for fruit crops and tomatoes, reviewed by Tsai-fua (1975), that high potassium depresses the uptake and translocation of calcium. Other such disorders were mentioned in section 4.4.1. It is generally agreed that it is the percentage saturation by K of the cation exchange capacity of the soil, rather its absolute value, which would indicate a danger of such antagonistic effects.

As a general principle, the deficiency of one nutrient element will result in other elements accumulating in crop tissues, often in the inorganic form. Thus, He *et al.* (1994) have shown that increasing K applications to cabbage up to 150 kg K_2O ha^{-1} (which was optimal for yield) reduced its nitrate concentration by about 50%.

Other elements

The importance of sulphur and sodium for flavour have been referred to in paras 4.4.3. and 4.4.4. respectively, and calcium-related quality problems in para 4.4.1. Truog *et al.* (1953) found that celery grown with sodium had a better (milder) flavour and was less stringy than when sodium was not given.

7. Interaction with pests, diseases, and environmental stress

This was a subject of an IPI Colloquium held in Turkey in 1976 (IPI, 1976). In the opening session, it was observed that there was a shortage of information on these interactions, probably because of the lack of cooperation between plant nutritionists and plant pathologists.

The proceedings contain very few references to vegetable crops, but certain general observations may be relevant. High nitrogen levels appeared to increase susceptibility of plants to obligate parasites, such as rusts, mildews, clubroot and viruses, but it tended to reduce susceptibility to facultative ones such as those causing necrotic leaf spots. Nitrogen form was important, ammonia being toxic to certain soil pathogens, and nitrate to others (Huber and Watson, 1974). These two forms can also have opposite effects on the same disease. Potassium generally increased resistance to disease, e.g. soft rot symptoms in brassicae (Leuchs, 1959) but in carrots it increased susceptibility to Centrospora acerina (Roll-Hansen, 1974). It helps to protect plants from environmental stresses, and of these, freezing is particularly important for temperate vegetables. Beringer and Trolldenier

(1978) have reviewed the effects of K on frost and drought resistance, which are physiologically related. See Perrenoud (1990) for a recent review of potassium effects on plant health. Calcium appears to have a protective effect against several diseases (Kiraly, 1976). Hahn (1985) reported greater susceptibility to fungal and bacterial pathogens for boron deficient vegetable crops in the (then) GDR. Graham and Webb (1991) have reviewed the effects of micronutrients on disease. They conclude that the effects are generally beneficial, at least over the deficiency range of the element.

As regards pests, mention has already been made that low-N brassicas appeal to pigeons. It might be thought that such plants, which contain high sugar levels, would also favour aphids, but Jones (1976) listed several cases (including peach and cabbage aphids on Brussels sprouts) in which N either increased aphid severity, or had no effect. He also cited many instances where organic matter incorporation had beneficial effects as regards pest attack.

In general, it appears that well-balanced mineral nutrition, such as leads to maximum yields but without luxury consumption, helps the growth of the crop to keep ahead of that of pests and diseases.

8. Crop specific fertilizer management and recommendations

8.1. Vegetables grown under temperate conditions

Table 8 shows recommendations currently in use in several countries for the major field vegetable crops grown: most correspondents pointed out that there is no official national set of figures. In Germany, for example, the various "Länder" (states) may have different systems, as is the case with the USA. Phosphate, potash, and magnesium recommendations mostly apply to sandy loam soils with "medium" levels of soil P, K, and Mg.

Table 8. Fertilizer recommendations for temperate vegetables in various countries (wherever there is a blank space, it means that no information is available).

8.1. Amaryllidaceae

Country	N	P_2O_5	K_2O	Mg
		kg ha^{-1}		
		Leek (*Allium ampeloprasum* L. *Porrum* group)		
Denmark	240*	90	240	30
Finland	100	150	145	
Germany	220* (60)	70	240	20
Netherlands	270*	75	200	60
Norway	170	135	200	
UK	100	150	125	0
USA	125	170	170	
Sweden	170	105	195	
Switzerland	120	60	180	30
		Onion (*Allium cepa* L. *cepa* group)		
Denmark	135*	90	220	25
Finland	70	150	100	
Germany	160* (60)	90	250	20
Netherlands	110	75	150	60
Norway	170	135	200	
UK	60	150	125	0
USA	100	140	140	
Sweden	120	125	195	
Switzerland	80	40	200	40

8.2. Gramineae

Country	N	P_2O_5	K_2O	Mg
		kg ha^{-1}		
		Sweet corn (*Zea mays* var. *Rugosa Bonaf.*)		
UK	75	50	50	0
USA	155	135	135	
Sweden	140	80	160	
Switzerland	120	60	180	30

8.3. Liliaceae

Country	N	P_2O_5	K_2O	Mg
		kg ha^{-1}		
		Asparagus (*Asparagus officinalis* L.)		
Germany	90* (90)	50	230	15
UK	50	75	25	
USA	60	140	140	
Sweden		30		
Switzerland	80	30	120	20

8.4. Chenopodiaceae

Country	N	P_2O_5	K_2O	Mg
		kg ha^{-1}		
		Red beet (*Beta vulgaris* var. *Esculenta* L.)		
Denmark	200*	80	240	30
Finland	70	80	110	
Germany	250* (60)	70	260	35
Norway	110	80	200	
UK	200	100	200	0
USA	100	110	110	
Sweden	150	115	230	
Switzerland	120	50	220	70
		Spinach (*Spinacea oleracea* L.)		
Germany	195* (30)	45	245	15
Netherlands	240*	75	200	60
UK	100	200	200	0
USA	125	140	140	
Sweden	100	105	195	
Switzerland	100	40	150	15

8.5. Compositae

Country	N	P_2O_5	K_2O	Mg
		kg ha^{-1}		
		Endive (*Cichorium endiva* L.)		
Germany	180* (60)	40	250	20
Netherlands	165*	125	100	60
Switzerland	100	50	180	30
		Witloof (Chicory, Radicchio) (*Cichorium intybus* L.)		
Germany	80* (60)	50	190	25
Netherlands	+	50	150	60
UK	75	150	150	0
Switzerland	0	50	150	30
		Lettuce (*Lactuca sativa* L.)		
Denmark	170*	70	180	15
Finland	100	80	100	
Germany	140* (30)	40	150	12
Netherlands	150*	125	150	60
Norway	110	135	150	
UK	150	250	100	
USA	80	170	170	
Sweden	100	70	135	
Switzerland	80	30	100	10

8.6. Cruciferae

Country	N	P_2O_5	K_2O	Mg
		kg ha^{-1}		
		Swede (Rutabaga) (*Brassica napus* L. *Napobrassica* group)		
Finland	110	90	180	
Norway	75	60	150	
UK	50	50	150	0
Sweden	140	105	200	
		Cauliflower (*Brassica oleracea* L. *Botrytis* group)		
Denmark	280*	90	240	25
Finland	145	60	110	
Germany	300* (60)	90	300	25
Netherlands	300*	75	200	60
Norway	240	80	240	
UK	200	75	125	0
USA	140	140	140	
Sweden	180	90	195	
Switzerland	130	50	180	30

8.6. Cruciferae (continued).

Country	N	P_2O_5	K_2O	Mg
		kg ha^{-1}		
		Cabbage (*Brassica oleracea* L. *capitata* group)		
Denmark	275*	90	305	30
Finland	200	115	170	
Germany	350* (90)	50	190	25
Norway	240	80	240	
UK	250	75	175	0
USA	140	140	140	
Sweden	250	140	290	
Switzerland	220	80	300	60
		Brussels sprouts (*Brassica oleracea* L. *Gemmifera* group)		
Denmark	250*	90	265	30
Germany	250* (90)	140	370	30
Norway	170	80	240	
UK	250	75	125	0
Switzerland	160	60	200	20
		Kohlrabi (*Brassica oleracea* L. *Gongylodes* group)		
Germany	200* (30)	80	210	15
Switzerland	120	60	180	50
		Broccoli (Calabrese) (*Brassica oleracea* L. *Italica* group)		
Denmark	220*	90	240	25
Germany	300* (60)	70	200	25
UK	200	60	75	
USA	200	140	140	
Switzerland	140	40	170	20
		Chinese cabbage (*Brassica rapa* L. *Pekinensis* group)		
Denmark	200*	70	220	20
Finland	130	70	120	
Germany	250* (60)	70	230	20
Norway	110	80	150	
UK	250	75	175	
Sweden	180	115	230	
Switzerland	120	60	200	30
		Turnip (*Brassica rapa* L. *Rapifera* group)		
Norway	110	60	150	
UK	50	50	150	0

8.6. Cruciferae (continued).

Country	N	P_2O_5	K_2O	Mg
		kg ha^{-1}		
		Radish (*Raphanus sativus* L.)		
Germany	100* (30)	40	180	20
Norway	75	60	100	
UK	25	25	100	
Switzerland	40	20	80	20

8.7. Umbelliferae

Country	N	P_2O_5	K_2O	Mg
		kg ha^{-1}		
		Celery (*Apium graveolens* L. var. dulce (Mill.) Pers.		
Denmark	230*	90	220	25
Finland	110	90	120	
Norway	110	100	200	
UK	75	125	300	
USA	154	200	200	
		Celeriac (*Apium graveolens* L. var. rapaceum (Mill.) Gaud-Beaup.		
Denmark	250*	90	280	40
Germany	220* (60)	140	330	20
Netherlands	220*	125	200	60
Norway	170	135	240	
Switzerland	130	50	200	30
		Carrot (*Daucus carota* L.)		
Denmark	120*	80	240	30
Finland	100	115	170	
Germany	100 (60)	70	230	21
Netherlands	80*	125	200	60
Norway	110	100	200	
UK	25	150	150	
USA	75	110	110	
Sweden	90	105	240	
Switzerland	130	60	220	40
		Parsnip (*pastinaca sativa* L.)		
Germany		80	300	30
UK	75	75	150	0
		Parsley (*Petroselinum crispum* (Mill.) Nyman ex A.W. Hill		
Germany		60	180	20
Switzerland	80	40	160	20
		Fennel (*Foeniculum vulgare* Mill.)		
Germany	170*	50	180	20

8.8. Leguminosae

Country	N	P_2O_5	K_2O	Mg
		kg ha^{-1}		
		Pea (*Pisum sativum* L.)		
Finland	40	45	30	
Germany	80*	50	120	25
Netherlands	50*	125	150	60
Norway	75	60	100	
UK	0	25	25	0
USA	60	90	90	
Switzerland	15	40	100	20
		Dwarf bean (*Phaseolus vulgaris* L.)		
Finland	40	60	75	
Germany	140*	60	190	15
Netherlands	165*	125	150	60
Norway	110	100	150	
UK	100	150	100	0
USA	70	70	70	
Sweden	180	90	195	
Switzerland	20	30	80	20
		Broad bean (*Vicia faba* L.)		
Netherlands	0-50	125	150	60
UK	25	150	100	0

* German, Danish and most Dutch N recommendations include the initial N_{min} value: see the source publication for details of sampling depth, etc.
+ see source publication.
Figures in brackets after the German N recommendations are the soil sampling depth (cm) for N_{min} measurements.

As already mentioned, some European countries have adopted the "N_{min}" approach to N fertilization, and where this is the case, as indicated by an asterisk, the figures shown include the amount found in the soil at planting or sowing time.

The figures for Denmark were supplied by J.N. Sørensen of the Danish Institute of Soil Science. There it is recommended for N to measure soil N_{min} before crop establishment, but they are experimenting with measurements made about eight weeks later. Splitting of N applications into several doses is recommended.

The Finnish figures were obtained from the Viljauuspalvelu (soil analysis service), 00410 Helsinki. N recommendations vary slightly with soil texture.

The German N recommendations are from Scharpf (1991), who gives full details of their N_{min} system. The P, K and Mg figures apply to class C (medium P, K, Mg analysis) soils in Bavaria (Anon., 1985). They should be multiplied by 1.5, 1.2, 0.5, or 0 respectively for class A, B, D and E soils (very low... very high).

The Dutch N figures are taken from Sieling (1992) which should be consulted for details of the N_{min} sampling system recommended in Holland. The P, K and Mg data are from Anon. (1984), which give adjustments to these levels for seven categories of P, K and Mg status of the soil.

In Norway there are no official recommendations. The very variable rainfall means that N and K leaching differs locally: spring N_{min} levels are so low that it is not considered worthwhile to measure them. The figures are from Balvoll (1989).

In the UK, the N_{min} method is rarely used: all the figures quoted are from MAFF (1994), which give the official ADAS recommendations. Those for N are for index 1 soils; higher or lower rates apply to index 0 and 2. Likewise the P, K and Mg figures would vary according to the level of these nutrients in the soil.

The USA figures are from Lorenz and Maynard (1988) p. 151, and are as used in the mid-Atlantic states. Values given there for low and high status soils have been averaged.

Sweden also has no official recommendations; those shown are as provided by "Hydro Supra" and were kindly passed on by G. Erlandsson of the Swedish University of Agricultural Sciences. The P_2O_5 amounts may be adjusted ± 25 kg and the K_2O amounts reduced by 35 kg according to soil P and K status. There is some interest among growers in the N_{min} system.

The Swiss recommendations are taken from Gysi *et al.* (1993), p. 77. The N recommendations apply to soil of "adequate N status", corresponding to about 120 kg mineral N ha^{-1}. This can be checked with a quick test. P and K recommendations are based on exports, and are under review.

The quantities of N, P_2O_5, K_2O, and Mg exported from the field with vegetable crops of given yields are shown in Table 9. These amounts do not include the non-marketable parts and therefore, are less than the total uptake of the crop. They should be used to determine the long-term nutrient balance for a farm.

Table 9. Amounts of nutrients removed from the field by vegetable cropping (from Gysi, 1993) (kg ha^{-1}).

If yields differ from these, removal figures should be adjusted proportionately. Crops marked * are taken from NVRS (1980). Yields shown are marketable parts: it is assumed that the residues remain in the field.

Crop	Yield, t ha^{-1}	N	P_2O_5	K_2O	Mg
Asparagus	6	20	6	15	1
Black radish	50	85	35	195	8
Broad bean*	16	80	30	60	-
Broccoli	15	80	30	85	4
Brussels sprouts	18	130	35	90	4
Carrots	50	80	40	175	9
Cauliflower	20	80	25	80	3
Celeriac	35	85	65	135	3
Chicory	50	10	3	10	1
Chinese cabbage	60	115	110	150	7
Chives	30	170	50	155	13
Courgette	45	115	25	190	9
Cucumber	20	20	10	35	2
Dwarf bean	25	95	25	75	6
Endive	30	85	40	125	3
Fennel	20	80	25	120	10
Kohlrabi	35	110	40	160	15
Lamb's lettuce	10	30	10	50	1
Leek	30	110	30	80	5
Lettuce	25	50	20	70	3
Onion	50	100	50	105	6
Parsnip*	44	146	80	220	-
Peas	10	105	25	35	3
Radish	40	70	25	120	3
Red beet	60	150	80	240	15
Red cabbage	45	110	30	145	8
Rhubarb	50	50	30	160	7
Scorzonera	25	55	45	95	6
Spinach	16	65	20	120	9
Summer cabbage*	62	210	48	210	-
Sweet corn	18	95	45	65	9
Swede (rutabaga)	60	250	60	175	-
Turnip	30	80	35	90	-
Winter cabbage	50	180	65	190	-

It is possible to make certain generalisations about individual crop species or families. For example:

- The *alliums* (leek, onions, chives, garlic) have thick, sparsely-branched roots without root hairs: they are concentrated in the top 20 cm of soil: this is thought to be the reason why, despite having a lower relative growth rate than most species, they are inefficient at taking up nutrients, especially P and K (Brewster, 1990). Certainly onions and leeks have proven to be very responsive to NP starter fertilizer (Plate 8), and this has reduced the amount of broadcast N required (Stone and Rowse, 1992). Onions are quite susceptible to copper and zinc deficiency, both of which cause twisting and chlorosis of leaves.
- Sweet corn requires relatively high temperatures and in Northern Europe the aim is to accelerate maturity. The work of Peck and MacDonald (1975) at Geneva, New York State, shows that young plants are responsive to high levels of P and K, and that P hastens maturity. As we have seen in other examples, response to these high levels of seed-bed P in such small plants indicates that placement of nutrients near the seed is desirable. Shrivelled kernels may indicate exhaustion of nitrogen. Sweet corn is susceptible to zinc deficiency (Lingle and Holmberg, 1957; Table 3) whereas lack of boron can cause barren or partly barren ears.
- Asparagus is a perennial crop whose shoots (or "spears") are harvested as they emerge from the soil in the spring. European yields are about 6 tonnes/ha (Gysi *et al.*, 1993) which would imply very low nutrient removals, but in the high radiation conditions of Arizona, with yields of 12 tonnes/ha, as much as 300 kg N/ha (applied in the irrigation water) has been found profitable (Gardner and Roth, 1989). Those authors found a critical N% in the fern of 3.5 in early summer, falling to 2.6 in late summer. These figures would probably apply elsewhere in the world.
- Red beet and spinach belong to the family *Chenopodiacae*, whose members are generally salt-tolerant. However, Greenwood *et al.* (1980a) showed that, despite belonging to the same family, their potassium requirements were opposite; spinach having a very large requirement and red beet a very low one. This is in spite of the fact that a red beet crop contains about three times as much K per hectare as a spinach crop. Strangely, these differences in responsiveness are not reflected in the national recommendations in Table 8.4. Their response to P was similar to that to K, i.e. spinach was extremely responsive and red beet not at all

(Greenwood *et al.*, 1980b). Spinach might be expected to respond well to an NPK starter fertilizer, but is usually grown in very close rows which do not permit the use of the drill unit shown in Plate 7. Excessive use of N results in a rapid build-up of nitrate in both crops (e.g. Fig. 6): for spinach, this is particularly undesirable when the produce is intended for baby food. Red beet quite often suffers from boron deficiency, which is manifested as black cankerous zones in the root tissue.

- Lettuce (family *Compositae*) is characterized by a high demand for phosphate when very young, and is very responsive to starter solutions containing N and P. Seedlings are sensitive to salinity, germination being completely prevented by an osmotic potential of -8 bars as compared with -16 bars for cabbage (Page and Cleaver, 1983). Nitrogen requirement is not large (about 150 kg/ha including N_{min}) but plants fail to heart if given insufficient N. If more than 50 kg/ha is broadcast as nitrate for drilled crops, regular watering is advisable until emergence is complete. A common nutritional problem with lettuce is tipburn (para 4.4.1. and Plate 5) which occurs unexpectedly and has been estimated to cause $ 2M loss/year in the UK alone (Collier and Tibbits, 1984). Choice of resistant cultivars, avoidance of soil compaction and excessive soil cation levels (K, Mg, NH_4), and early harvesting all help to contain the problem. Lettuce has also been known to suffer molybdenum deficiency on acid soil and in slightly acid peat composts.
- *Cruciferae*, including particularly the *Brassica* family, have a very high nitrogen requirement but are generally unresponsive to P and K (Greenwood *et al.*, 1980a and 1980b). They have not been responsive to NP starter solutions in the UK, whether drilled or transplanted. Growers should look out for signs of magnesium, sulphur, and boron deficiency, and periodically have leaves analysed for these elements. *Brassicas* leave large residues in the field, which quickly rot down and mineralise in warm soil. Hence if a second crop per year is taken (e.g. of cauliflowers) it will require much less fertilizer than the first (Rahn *et al.*, 1992). This is a situation where a banded application of N providing a concentration round the plants equivalent to a broadcast application of 100 kg N/ha would probably be enough to supply them until the residues of the previous crop have mineralised. If the bands cover 50% of the soil surface, this would be an average application of 50 kg N/ha. Cauliflowers are the vegetable crop most sensitive to molybdenum deficiency, which causes "whiptail" (see Table 3).

- Carrots, celery, parsnip, etc., belong to the family *Umbelliferae*. Carrots, and to a lesser extent parsnip, require little N: not only is emergence depressed, but so is the root/shoot ratio, so that abundant top growth may not signify an equally heavy crop of roots. Carrots are extremely responsive to P when young, but an experiment at Wellesbourne, UK, showed that a two-fold response to P in mid-July had completely disappeared by late October. Hence an NP starter fertilizer is likely to be most useful for early carrots.

- Members of the family *Leguminosae* (peas, beans, etc.) are able, by virtue of the symbiotic bacteria on their roots, to fix atmospheric nitrogen in organic forms. For peas (*Pisum sativum*) and broad beans (*Vicia faba*), the bacterium concerned is *Rhizobium leguminosarum*, which is common in temperate soils so that these species very rarely respond to fertilizer N in temperate areas. Dwarf or snap beans, however (*Phaseolus vulgaris*) and runner beans (*Phaseolus coccineus*) are associated with *Rhizobium phaseoli*, which is less predictable as a source of nitrogen. Unless deliberately inoculated, therefore, they should receive about 150 kg N/ha as fertilizer.

- Peas: Fertilizer nitrogen may actually depress the yield of peas and delays the formation of root nodules. Attempts to restore greenness of pea crops affected by the pea weevil (*Sitona lineatus*) or by waterlogging by applying nitrogen have rarely been successful. Peas are unresponsive to P but K is very important, and up to 50 kg/ha of K_2O can safely be combine-drilled at rows widths up to 20 cm. Amounts in excess of this (e.g. on low-K soils) should be broadcast. Broadcast P and K should be deeply incorporated into the soil well in advance of drilling.

- Dwarf or snap beans: Taylor (personal communication) considers that the nitrogen requirement of the crop can be satisfied more reliably by Rhizobium than by fertilizer provided (a) that the correct strain of Rhizobium is used (which may be cultivar-specific), and (b) a small amount of fertilizer N (about 40 kg ha^{-1}) is broadcast on the seed-bed to cover the period before the roots nodulate. He found that nitrogen responses were small in UK except on sandy soils.

8.2. Fertigated vegetables in arid and semi-arid zones

8.2.1. Principles of combined irrigation and fertilization

8.2.1.1. Introduction

Irrigation and fertilization are the most important management factors by which farmers control plant development, and fruit yield and quality. The introduction of trickle irrigation and fertilization (fertigation) (Goldberg *et al.*, 1976; Dasberg and Bresler, 1985) opened up new possibilities for controlling water and nutrient supply to crops, and maintaining the desired concentration and distribution of ions and water in the soil. The improved control under drip fertigation compared with sprinkler irrigation and broadcast fertilization is due to several factors: (a) accurate and uniform application under all circumstances; (b) application of nutrients to the wetted area only, where the active roots are concentrated; (c) easy adaptation of amounts and concentrations of specific nutrients to crop requirements according to the stage of development and climatic conditions; (d) crop foliage is kept dry, thus retarding the development of plant pathogens (Yarwood, 1978) and avoiding leaf burn; (e) convenient use of compound, ready-mix and balanced liquid fertilizers with minute concentrations of minor elements which are otherwise very difficult to apply accurately to the field.

8.2.1.2. Quantity considerations

To exploit the advantages offered by fertigation systems, two plant-related quantity factors must be known:

a. Expected dry matter production rate by the plant and the optimal nutrient concentration in plant tissues which together define the daily nutrient consumption rate during the growing season that results in maximum yield and product quality. Such a function [Q(t)] determines the minimal daily application rate of a given nutrient which is required to maintain a steady state nutrient concentration in the soil. The actual fertilization rate should account for the fertilizer use efficiency by the plants ($EF<1$) and should therefore be Q/EF. Under good management EF exceeds 0.80 (Shevah and Waldman, 1989).

b. Optimum daily water consumption rate during the season which facilitates uninhibited photosynthesis by the plants. The transpiration function depends on meteorological conditions and plant characteristics (Stanhill, 1985; Hatfield and Fuchs, 1990). The actual irrigation rate exceeds the transpirational demand as it accounts also for evaporation from the soil surface and leaching of salts accumulated in the root zone.

8.2.1.3. Intensity considerations

There are two major intensity factors that must be known for proper fertigation management:

a. Target root density distribution in the soil and total root weight.

b. The nutrient concentrations in the soil solution enabling plants to absorb nutrients according to the prescribed Q(t). Root and nutrient concentrations have complementary effects, since uptake rate is the integral of the flux x root surface area (or length) in a given soil sub-volume, over the total number of sub-volumes in the soil profile. The flux F (mol [cm root]$^{-1}$ s^{-1}) is determined by the nutrient concentration in the soil solution at the root surface, Cr (mol L^{-1}), as shown by the Michaelis-Menten equation:

$$F = F_{max}\, C_r/(K_m + C_r) \qquad [1]$$

where F_{max} (mol [cm root]$^{-1}$ s^{-1}) and Km (mol L^{-1}) are plant coefficients obtained in flowing or well stirred nutrient solution experiments. Representative values of K_m and F_{max} (eq. [1]) for various crops are presented in Table 10.

Table 10. Values of F_{max} and K_m of NO_3, P and K for several plant species using intact plants in well stirred solution culture[a].

Crop	F_{max} (mol cm^{-1} s^{-1}x10^{13})			K_m (mol L^{-1}x10^{6})			Ref.[c]
	NO_3	P	K	NO_3	P	K	
Maize	1.16	0.50	5.02	10	3.0	16	1
	-	6.1	-	-	1.0	-	4
Soybean	-	0.10	-	-	2.0	-	1
Wheat	-	0.18	0.88	-	6.0	7	1
Tomato[b]	5.1	-	-	258	-	-	19
Barley	-	-	34.9	-	-	15	36

[a] Subject to the following assumptions: root radius = 0.02 cm; C_{min} in Barber's data disregarded.

[b] Recalculated.

[c] Ref.: Barber (1984); Bar-Yosef (1971); Ben Asher *et al.* (1982); Fried and Broeshart (1967).

The integration of uptake over the root zone and eq. [1] form the basis for most models simulating nutrient uptake and plant growth (e.g. Tillitson *et al.*, 1980; Marani and Baker, 1981; Jones and Kiniry, 1986, Fishman and Bar-Yosef, 1995). Such models can be modified into fertigation decision tools, by comparing the computed uptake rate based on current soil variables, and the target uptake rate at each time step during the simulation process. If the computed uptake and the target Q(t) do not match, a correction (e.g. enhanced or reduced fertigation) must be applied.

8.2.1.4. Importance of flux-concentration relationships

Even without management models, equation [1] can be used to define some threshold concentrations in the irrigation water. When $C_r > K_m$, the increase in flux (F) due to an incremental increase in C_r diminishes rapidly, and hence it is unadvisable to maintain at the root surface a concentration which sustains a F which exceeds $0.75F_{max}$ (namely, $C_r = 3K_m$). Above this threshold concentration any unexpected increase in C_r may cause pollution and reduced influx of other nutrients (Fried and Broeshart, 1967; Fishman and Bar-Yosef, 1995).

Another possible application of eq. [1] is to estimate the minimal active root weight (or length) (Rm) as a function of time, which is required to facilitate uptake rates according to Q(t):

$$Rm = Q(T)/F_{max} \qquad [2]$$

The concentration of a non-adsorbing nutrient in the irrigation water (C_w) is a first approximation of its concentration in the bulk soil solution (C_b), but not at the root surface. For adsorbing nutrients (P, K), C_w should be corrected for the expected adsorption, based on the partitioning function of the nutrient between the solution and solid phases in the soil. The difference between C_r and C_b stems from the rapid depletion of nutrients in the vicinity of the root, and the slower transport of the nutrients from the bulk soil to the root surface. The difference between C_w and C_b diminishes as fertigation frequency increases. Assuming no mass flow and steady state concentrations in the soil, the relationship between C_b and C_r is defined by eq. [3], which was derived from Olsen and Kemper (eq. [61], 1968), and by eq. [1]:

$$C_b = C_r\,[1.+S/(K_m + C_r)] \qquad [3]$$

Here, $S = F_{max} \ln(b/a)/(6.28\ Dp)$, b and a are the mean midway distance between roots and root radius (cm), respectively, and Dp ($cm^2\ s^{-1}$) is the diffusion coefficient in the soil solution, defined as $Dp = K\ D_o \exp(\alpha\ \theta)$ (Olsen and Kemper, 1968). Here, D_o is the diffusion coefficient in water, θ is the volumetric water content and α (~10) and K (~0.001 to 0.005) are soil constants; K decreases as the soil surface area increases. Under regular fertigation conditions, S may vary between 100 K_m and 0.01 K_m. For example, when a = 0.02 cm, b = 2.0 cm, Dp = 1.0 E-8 cm^2 s^{-1} (a clay soil) and $F_{max}(NO_3)$ = 5.1 E-13 mol cm^{-1} root s^{-1} (tomato, Table 10), S = ~30 mM, and is ~115-fold greater than $K_m(NO_3)$ of tomato. Under such conditions, and assuming $C_r = K_m$, eq [3] predicts that the C_b/C_r ratio is ~50. Accepting that C_w=C_b, the NO_3 concentration in the irrigation water should therefore be 50 K_m. For thicker (a = 0.04 cm) and denser (b = 0.2 cm) roots, which grow in a sandy soil (D_p = 2.7 E-6 cm^2 s^{-1}), and for the same F_{max}, S = ~50 μM, which is 65-fold smaller than the $K_m(NO_3)$ of tomato. In this case, the C_b/C_r ratio is ~1.1 (eq [3]), and C_w is a good estimate of NO_3 concentration at the root surface.

Since mass flow was assumed to be zero in the above approximations, the actual C_b which is required to furnish a certain C_r is less than estimated above.

In several works the parameters in eq [1] were determined in unstirred solutions, or in growth substrates. Under such circumstances, K_m is expressed as concentration in the bulk soil solution (K_{ms}, Table 11). The disadvantage of this approach is, that K_{ms} depends not only on the crop properties, but on soil characteristics and fertigation management also. Comparison between $K_{ms}(N)$ of tomato plants grown in sand (Table 11) and K_m (Table 10) shows that the former is approximately 10-fold greater than the latter; F_{max}(tomato) in the soil is two-fold greater than F_{max} in well stirred solution, which is a surprisingly good agreement. The K_{ms}/K_m ratio of 10 indicates that C_r in sand is approximately one tenth of C_b, or C_w. This ratio is within the C_b/C_r ratios range estimated above.

Table 11. Michaelis-Menten constants for N and P of pepper and tomato plants grown in unstirred solution cultures and in two growth substrates.

Crop	Nutrient	F_{max}[a] (mol cm^{-1} s^{-1} 10^{13})	K_{ms}[a] (μM)	System	Ref.
Pepper	N	14.0	550	Unstirred solution[b]	2
	P	17.0	25	Unstirred solution	2
Tomato	N	11.0	3000	Sand	13
	P	1.8	320	Rockwool	15
	K	3.0	1000	Aerophonic	3

a To distinguish from F_{max} and K_m in well stirred solutions. To transform from mol g^{-1} to mol cm^{-1}, a root radius of 0.02 cm was assumed.

b NH_4-N:NO_3-N in solution = 1:3; 20- to 30-day-old seedlings.

8.2.1.5. Coupling quantity and intensity factors

Under ideal conditions, the quotient Q(t)/(daily irrigation rate) (=C) should equal the above estimated C_b. The daily irrigation rate (mm/day), is determined according to estimated reference evapotranspiration multiplied by a time dependent crop coefficient (Hatfield and Fuchs, 1990). The irrigation scheduling is determined according to the soil water potential, usually monitored with tensiometers at reference points in the rhizosphere (Martin *et al.*, 1990). Reference daily evapotranspiration can be estimated from class A pan evaporation or calculated from meteorological data (Hatfield and Fuchs, 1990). When irrigation quantity is large (e.g. in summer) and the root system is confined (e.g. high frequency drip irrigation), C may be too low to furnish the required uptake rate by the plants, as the integral of flux x root length is too low. In this case, the nutrient application rate should be raised above the target Q(t). This operation is wasteful and environmentally undesirable. To avoid such problems, plants can be grown with larger root systems, such that lower C_r may be sufficient to maintain the target Q(t). Expanded soil root volumes have a high buffer capacity for water and nutrients, which reduces possible stresses stemming from unexpected disrupted supply. However, large root volumes cannot be rapidly enriched or depleted of nutrients, thus accommodating easy control of uptake according to time-specific plant needs. Plants with large root volumes usually have lower water and nutrient use efficiencies than those with confined root systems.

8.2.1.6. Root growth in soils

Factors affecting root growth depend on carbohydrate and other canopy-synthesized products, and on physical and chemical conditions prevailing in the soil root zone. Primary factors affecting root proliferation are (i) soil resistance to root penetration, (ii) oxygen, P and N concentrations in the soil, and (iii) the presence of elements toxic to root growth. Factor (i) is strongly dependent on soil water content (θ) via the effect of θ on soil strength, O_2 concentration in the soil, and O_2 and nutrient transport to roots (Bar-Yosef and Lambert, 1981). Factors (i) and (ii) explain how fertigation rate and frequency, which determine θ and nutrient concentrations and distributions in the wetted zone (Bresler, 1975), affect root growth and spatial and temporal distribution in the soil. Characteristic root distributions in soil of drip fertigated tomato, pepper, muskmelon and sweet corn, which gave high yields, are presented in Tables 12 and 13. The four root systems were bounded within a soil cylinder 40 cm in radius, which coincided with the lateral water front position in the soils (data not shown). The depth of tomato and pepper root systems was shallower than sweet corn and muskmelon, apparently due to differences in root growth characteristics. The experimental root weight of tomato (Table 12) can be compared with the theoretical minimum root weight which is necessary to furnish the tomato plant with its maximum Q(N) (eq. [2]). Assuming a Q(N) of 2.5 kg N ha^{-1} day^{-1} (see below), $F_{max}(NO_3)$ of (5 mol cm^{-1} s^{-1}) E-13 (Table 10) and 8% root dry matter content, a minimum dry root weight of 400 kg ha^{-1} is obtained. The close agreement between the calculated and experimental root weights indicates that at the time of peak N consumption rate, the roots of drip fertigated tomato plants must absorb N at a flux which approaches its maximum capacity. To achieve F_{max}, the N concentration in the soil solution at the root surface must be ~3 K_m.

When calculating the minimal root weight for N uptake by sweet corn (Q=6 kg N ha^{-1} day^{-1}) (eq. [2]), and using the available F_{max} of grain corn (Table 10), a fresh root weight of 54,000 kg ha^{-1} is obtained. This root weight is appreciably higher than the sweet corn fresh root weight which was found under field conditions (9000 kg ha^{-1}, Table 13). The discrepancy may indicate that sweet corn, which has a much shorter growth season, might have a considerably higher F_{max} and lower K_m than grain corn.

It is noted that the presented root weight of pepper plants is appreciably more than the dry tap root weight of chili pepper (600 kg ha^{-1} at a comparable plant age) reported by Beese *et al.* (1982). However, total dry matter production in the chili pepper was also considerably lower than in the current case. The presented root weight of tomato plants is similar to previously published data (Bar-Yosef, 1990).

8.2.2. Managing vegetables fertigation

8.2.2.1. N, P, K target consumption rates [Q(t)] and supply

Daily nutrient uptake rates that result in optimum yield and product quality [Q(t)] are crop specific and depend on climatic conditions, but are independent of soil characteristics and of irrigation technique. Optimum N, P, K consumption rate vs. time functions for several vegetables grown under normal weather conditions characteristic of the Middle East region, and the conditions pertinent to their derivation, are presented in Tables 14, 15 and 16, respectively.

Table 12. Root distribution in a sandy soil and total root weight of drip fertigated pepper and greenhouse tomato plants which gave optimal yields. Note the different units of root density, presented in their original form[a].

	Pepper[c] Lateral distance (cm)[b]				Tomato Lateral distance (cm)[b]				
Depth (cm)	0-10	11-20	21-30	31-40	0-10	11-20	21-30	31-40	41-50
	% of total dry root wt in sampled grid				mg dry root/kg dry soil				
0-10	15	12	11	5	320	87	39	9	103
11-20	6	11	7	6	45	72	63	36	103
21-30	5	8	9	4	45	34	43	85	62
31-40	2	1	2	2	28	45	60	75	63
41-50	-	-	-	-	22	60	15	28	22
51-60	-	-	-	-	1	1	1	1	1
Total dry roots weight[c]:	1900 kg ha^{-1}				400 kg ha^{-1}				

[a] *Sources*: Pepper: Bar-Yosef (1991); tomato: Bar-Yosef *et al.* (1992).

[b] From the stem towards the edge of the bed, perpendicular to the row.

[c] Plants stand: pepper 100,000; tomato 23,000 plants/ha.
Sampling times: pepper 120, tomato 90 days after planting.

Table 13. Relative root density[a] distribution in the soil[b] and total fresh root weight[c] of drip fertigated sweet corn and muskmelon plants which gave optimal yields.

Sweet corn				
	Lateral distance (cm)[d]			
Depth (cm)	0-10	11-20	21-30	31-40
	Relative root density (%)			
0-10	48	94	47	77
11-20	100	84	82	104
21-30	90	78	110	50
31-40	67	42	52	50
41-50	30	50	58	36
51-70	11	24	9	28
71-90	10	5	6	0
Total fresh roots weight:	9000 kg ha^{-1}			

Muskmelon			
	Lateral distance (cm)[d]		
Depth (cm)	0-10	11-20	21-30
	Relative root density (%)		
0- 10	100	54	50
11- 25	73	54	46
26- 40	19	42	35
41- 60	92	35	42
61- 80	38	38	23
81-100	53	23	7
Total fresh roots weight:	1000 kg ha^{-1}		

[a] Relative root density = root density (mg dry root/kg soil) in a given soil cube/root density in a reference soil cube. The reference root density is: 133 mg dry root/kg soil for sweet corn and 13 mg dry root per kg soil for muskmelon.

[b] Sweet corn in loess soil; muskmelon in sandy soil.

[c] Total root weight was estimated by multiplying root density by soil weight represented by the soil cube and summing over the sampled soil volume.

[d] From the stem towards the edge of the bed, perpendicular to the row.

Source: Bar-Yosef and Sagiv (1985).

Table 14. Daily nitrogen consumption rate by various vegetable crops grown under drip fertigation as a function of time after emergence or planting.

Days after emergence or planting	Processing tomatoes	Greenhouse tomatoes	Fresh tomatoes	Bell pepper a	Bell pepper b	Eggplant	Potatoes
				kg N ha^{-1} day^{-1}			
1- 10	0.10	1.00	0.30	0.10	0.10	0.05	0.25
11- 20	0.50	1.00	0.30	0.60	0.50	0.10	0.35
21- 30	1.00	1.00	0.30	2.30	1.50	0.20	0.40
31- 40	2.80	2.00	0.40	4.00	1.60	0.25	2.10
41- 50	4.50	2.50	0.40	4.50	1.70	3.20	2.00
51- 60	6.50	2.50	0.45	5.50	1.60	2.90	2.10
61- 70	7.50	2.50	0.50	6.00	1.70	0.25	2.90
71- 80	3.50	2.50	1.70	2.00	2.60	0.25	2.20
81- 90	5.00	1.50	2.80	1.00	2.80	0.25	1.40
91-100	8.00	1.50	1.30	4.00	2.50	0.25	1.50
101-110	-	1.00	2.70	1.00	2.50	0.25	0.80
111-120	-	1.00	4.60	-	1.50	1.20	1.00
121-130	-	1.50	3.90	-	-	2.40	-
131-150	-	1.50	2.70	7.00	-	2.60	-
151-180	-	4.00	-	-	-	2.30	-
181-220	-	2.00	-	-	-	1.90	-
Total (kg N ha^{-1})	393	450	250	380	205	290	170

Table 14. Continued (Crop and site specific information).

	Processing tomatoes	Greenhouse tomatoes	Fresh tomatoes	Bell pepper a	Bell pepper b	Eggplant	Potatoes
Variety	VF M82-1-2	F-144 (Daniela)	675	Maor		Black Oval	Desirea
Seeding/ planting	27 Mar+	25 Sept++	18 Sept++	26 Aug+	14 Jul+	10 Sept++	19 Feb+
Harvesting	18 Jul	Selective	Selective	Selective		Selective	1 Jul
Plants ha^{-1}	50,000	23,000	12,000	90,000	100,000	12,500	-
Soil	Clayey	Sandy	Sandy	Sandy		Sandy	Sandy
Marketable yield (t ha^{-1})	160	195	127	65	75	51	57
Reference	24	14	10	47	5	6	29

+ Seeding ++ Planting

Table 14. Daily N consumption rate by various vegetable crops often grown under drip irrigation, as a function of time after emergence or planting.

Days after emergence or planting	Lettuce	Celery	Chinese cabbage	Broccoli	Sweet corn	Carrot	Muskmelon
				kg N ha^{-1} day^{-1}			
1- 10	0.15	0.17	0.74	0.02	0.50	0.45	0.15
11- 20	0.45	0.21	1.11	0.07	1.00	0.87	0.20
21- 30	3.00	0.70	1.85	1.08	1.50	0.54	0.35
31- 40	3.40	0.88	2.96	1.22	3.50	0.56	0.90
41- 50	2.20	1.03	2.24	1.75	4.50	0.93	1.30
51- 60	1.80	0.99	2.70	1.04	6.00	0.71	2.50
61- 70	-	0.99	1.08	3.02	4.00	1.19	4.30
71- 80	-	0.83	0.84	3.41	3.00	1.09	2.40
81- 90	-	0.83	0.37	2.79	-	1.20	1.20
91-100	-	1.00	-	2.09	-	1.18	1.00
101-110	-	1.47	-	0.93	-	1.54	0.50
111-120	-	1.78	-	0.20	-	2.03	0.30
121-130	-	2.00	0.30	0.18	-	2.23	-
131-140	-	2.25	0.07	0.15	-	2.34	-
141-150	-	-	-	0.06	-	3.83	-
151-160	-	-	-	-	-	3.80	-
161-170	-	-	-	-	-	3.47	-
Total (kg N ha^{-1})	110	150	111	202	240	279	151

Table 14. Continued (Crop and site specific information).

	Lettuce	Celery	Chinese cabbage	Broccoli	Sweet corn	Carrot	Muskmelon
Variety	Iceberg	Florida	Kazomi	Woltam	Jubilee	Buror	Galia
Seeding/ planting	5 Nov+	10 Oct+	4 Nov+	30 Aug++	15 Apr++	11 Oct++	14 Jan
Harvest date	25 Jan	27 Feb	19 Jan	17 Jan	5 Jul	5 Apr	Selective
Plants ha^{-1}	100,000	90,000	80,000	33,000	75,000	400,000	25,000
Soil	Sandy	Loamy	Loamy	Loamy	Loamy	Loamy	Sandy
Marketable yield ($t\ ha^{-1}$)	45	65	82	13	28	85	56
Reference	9	27	50	26	49	51	48

+ Seeding ++ Planting

Table 15. Daily P consumption rate by various vegetable crops grown under drip fertigation as a function of time after emergence or planting.

Days after emergence or planting	Processing tomatoes	Greenhouse tomatoes	Fresh tomatoes	Bell pepper a	Bell pepper b	Eggplant
				kg P ha^{-1} day^{-1}		
1- 10	0.02	0.10	0.01	0.01	0.01	0.01
11- 20	0.05	0.10	0.02	0.10	0.10	0.01
21- 30	0.16	0.10	0.03	0.25	0.10	0.01
31- 40	0.19	0.20	0.03	0.35	0.20	0.01
41- 50	0.75	0.40	0.03	0.40	0.25	0.02
51- 60	0.80	0.60	0.04	0.20	0.35	0.08
61- 70	1.80	0.30	0.04	1.00	0.45	0.09
71- 80	0.50	0.30	0.18	0.20	0.35	0.05
81- 90	0.50	0.30	0.22	0.50	0.35	0.05
91-100	0.89	0.10	0.10	0.50	0.35	0.05
101-110	-	0.10	0.30	0.20	0.25	0.09
111-120	-	0.10	0.60	0.10	0.25	0.15
121-130	-	0.20	0.45	0.10	0.10	0.27
131-150	-	0.35	0.17	0.30	-	0.31
151-180	-	0.50	-	-	-	0.38
181-220	-	0.30	-	-	-	0.35
Total (kg P ha^{-1})	59	65	24	42	31	33

Table 15. Daily P consumption rate by various field crops often grown under drip irrigation, as a function of time after emergence or planting.

Days after emergence or planting	Lettuce	Celery	Chinese cabbage	Broccoli	Sweet corn	Carrot	Muskmelon
				kg P ha^{-1} day^{-1}			
1- 10	0.01	0.03	0.10	0.00	0.10	0.06	0.03
11- 20	0.10	0.04	0.16	0.01	0.15	0.16	0.03
21- 30	0.50	0.11	0.31	0.12	0.20	0.12	0.07
31- 40	0.60	0.08	0.51	0.13	0.55	0.12	0.18
41- 50	0.55	0.20	0.87	0.20	0.85	0.19	0.25
51- 60	0.45	0.23	0.81	0.13	1.15	0.20	0.25
61- 70	-	0.35	0.45	0.36	0.80	0.29	0.35
71- 80	-	0.29	0.28	0.46	0.20	0.27	0.45
81- 90	-	0.39	0.28	0.38	-	0.27	0.43
91-100	-	0.17	-	0.32	-	0.24	0.27
101-110	-	0.18	-	0.18	-	0.30	0.13
111-120	-	0.30	-	0.09	-	0.59	0.07
121-130	-	0.54	-	0.09	-	0.58	-
131-140	-	0.69	-	0.04	-	0.91	-
141-150	-	-	-	0.01	-	1.32	-
151-160	-	-	-	-	-	0.88	-
161-170	-	-	-	-	-	0.81	-
Total (kg P ha^{-1})	22	36	29	26	40	73	25

Table 16. Daily K consumption rate by various vegetable crops grown under drip fertigation as a function of time after emergence or planting.

Days after emergence or planting	Processing tomatoes	Greenhouse tomatoes	Fresh tomatoes	Bell pepper a	Bell pepper b	Eggplant
			kg K ha^{-1} day^{-1}			
1- 10	0.10	2.00	0.40	0.01	0.10	0.00
11- 20	0.30	4.00	0.50	1.00	0.90	0.00
21- 30	2.00	3.50	0.50	4.00	1.25	0.30
31- 40	2.30	3.50	0.50	7.00	1.25	0.80
41- 50	8.00	5.50	0.55	7.00	2.50	4.90
51- 60	8.50	5.50	0.55	8.00	4.50	7.20
61- 70	9.00	6.00	0.60	8.00	5.00	1.30
71- 80	4.50	4.00	2.20	3.00	4.50	0.50
81- 90	9.20	6.00	4.80	3.00	3.50	0.50
91-100	9.00	0.10	2.90	8.00	5.00	0.50
101-110	-	0.10	5.70	6.00	5.50	2.00
111-120	-	1.00	7.80	1.00	3.00	3.00
121-130	-	1.00	7.00	0.30	-	3.00
131-150	-	1.30	2.00	0.80	-	3.00
151-180	-	3.80	-	-	-	1.60
181-220	-	3.00	-	-	-	1.60
Total (kg K ha^{-1})	520	710	370	580	370	380

Table 16. Daily K consumption rate by various field crops often grown under drip irrigation, as a function of time after emergence or planting.

Days after emergence or planting	Lettuce	Celery	Chinese cabbage	Broccoli	Sweet corn	Carrot	Muskmelon
				kg K ha^{-1} day^{-1}			
1- 10	0.20	0.21	1.70	0.01	1.00	0.40	0.10
11- 20	0.50	0.24	2.80	0.02	1.50	0.88	0.25
21- 30	5.10	1.33	4.50	0.74	4.50	0.60	0.60
31- 40	7.80	1.52	7.20	0.91	5.80	0.60	1.45
41- 50	8.20	2.56	5.25	1.35	7.20	0.99	3.00
51- 60	3.20	2.78	5.52	3.04	3.80	0.98	6.00
61- 70	-	4.11	1.37	4.34	6.20	1.62	7.00
71- 80	-	4.05	0.01	3.95	2.00	1.57	8.00
81- 90	-	5.56	-	4.09	-	1.72	7.50
91-100	-	4.04	-	3.13	-	2.14	3.50
101-110	-	5.00	-	2.74	-	2.80	1.00
111-120	-	8.60	-	0.96	-	5.73	0.05
121-130	-	8.50	-	0.48	-	7.00	-
131-140	-	10.35	-	-	-	9.67	-
141-150	-	-	-	-	-	11.66	-
151-160	-	-	-	-	-	10.19	-
161-170	-	-	-	-	-	1.86	-
Total (kg K ha^{-1})	250	224	219	165	320	604	385

Considerable differences in uptake rate and in the time at which maximum consumption rate occurs exist among crops and among varieties of the same species (e.g. processing, glasshouse, and open-field tomatoes). In some cases, the consumption function is not monotonic, and exhibits sharp variation at critical physiological stages. Ignoring temporal variations in uptake rate may lead to over fertilization, and consequently to salinity build-up, reduced intake of other nutrients (Fried and Broeshart, 1967) and contamination of the environment. Sub-optimal supply may result in depletion of nutrients from the soil and inadequate uptake rate.

Extrapolation of the presented NPK uptake data to environmental conditions much different from those specified (e.g. different temperatures or radiation intensities) should be done carefully and treated only as a first approximation.

8.2.2.2. Nutrient concentrations in irrigation and soil solutions

The suitability of given nutrient concentrations in the irrigation water can be evaluated if the aforementioned root parameters are known. Let us consider as an example a fresh tomato (cv. 650) crop grown in a sandy soil and found at a growth stage of 100 days after planting, at the beginning of January.

According to Table 14, the target N consumption rate (Q_N) of this cultivar at this time is 2.7 kg N ha^{-1} d^{-1}. Suppose that the evaporation from class A pan at that time is 3 mm d^{-1} and the crop coefficient is 1 (= 30 m^3 ha^{-1} d^{-1}). Supplying the N through the water yields a concentration (=C_b) of 6.4 mM N. The question is whether this concentration is appropriate, namely, will it allow the plants to absorb the amount of N which was added to the soil. To answer this question we need to estimate N concentration at the root surface (C_r) and compare it with K_m. In sandy soils, a C_r/C_b ratio of 0.1 was shown to be a sound approximation. If so, C_r is expected to be ~0.64 mM N, which is about two-fold greater than K_m of tomato (Table 10). Recalling that C_r should preferably be between 1 and 3 K_m, it can be concluded that the obtained concentration of 6.4 mM N in the irrigation water can safely be used.

A more detailed analysis of the suitability of this concentration would involve the following steps: (i) calculate F_N (eq.[1]) according to F_{max}, K_m (Table 10) and C_r (= 4.2 10^{-7} gN cm^{-1} root d^{-1}). (ii) Evaluate tomato plant root weight from data in Table 12, assumed root dry matter content (~5%) and estimated root radius (0.02 cm) (= 6.4 10^9 cm root ha^{-1}). (iii) Multiply F_N by root length to obtain the rate of N uptake (= 2.7 kg N ha^{-1} d^{-1}). The excellent agreement between the calculated uptake and target consumption rates supports the conclusion obtained above regarding the suitability of 6.4 mM N in the irrigation water. If the crop had a root length which is 70% of the above, the agreement between calculated and target uptake rates would be less impressive, even though 30% difference is still reasonable. If the root system is even smaller and the calculated uptake deviates by more than 30%, N concentration in the irrigation water should be increased, but should not surpass 40 K_m, to increase F_N. Immediate action should be taken to increase the plant's root length, as otherwise the excess N application rate over the target uptake rate (Q_N) will cause environmental damage.

If plant parameters are not available, one should take care that Q(t)/(daily irrigation rate) does not exceed the salinity threshold of the crop of interest, above which yield and fruit quality decline (Hoffman *et al.*, 1990). An alternative approach to the direct evaluation of optimal C_w, is to use empirical functions relating C_w to uptake rate by whole plants. These functions are specific to soil, crop, plant age and irrigation regime. Two examples of such functions, for tomato and pepper, are presented in Figs. 7 and 8. According to Fig. 7, $C_w(NO_3)$ supplied to tomato plants grown in a sandy soil and having a root system bounded by a soil cylinder of 30 cm radius and 60 cm depth should not exceed 100 and 150 mg N L^{-1} at the age of 70 and 140 days after seeding, respectively. These concentrations correspond to ~2K_{ms} and ~3K_{ms} (see Table 11), and to ~27K_m and ~38K_m (see Table 10), respectively. According to Fig. 8, the optimal C_w(N) of 76-96 day old pepper plants grown in two sandy soils is ~80 mg L^{-1}. The corresponding optimal C_w(K) of the same pepper is 100 mg K L^{-1} (Fig. 8). The condition that C_w x (daily irrigation rate) = Q(t)/EF must be preserved also when using the empirical approach.

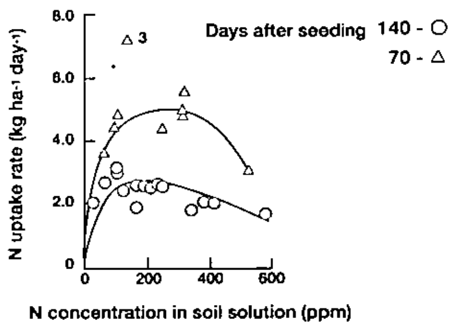

Fig. 7. Mean daily nitrogen uptake determined from plant analyses over the time intervals 60 to 73 and 138 to 165 days after seeding as a function of average NO_3-N concentration in the solution of a soil cylinder bounded by a radius and depth of 30 and 60 cm, from the trickler, respectively, at specified times. The curves were fitted by hand (*Source*: Bar-Yosef and Sagiv, 1982a).

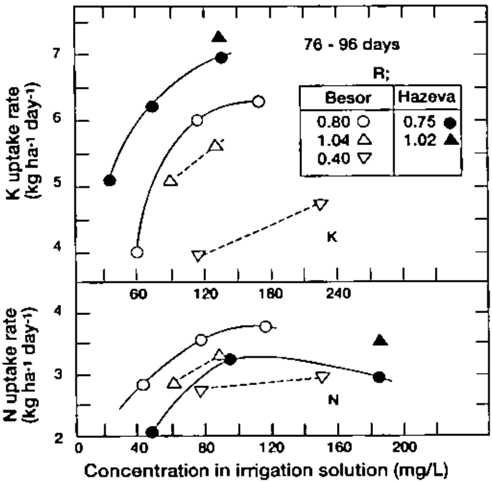

Fig. 8. Rates of N and K uptake by pepper plants as a function of their concentration in the irrigation water 76 and 96 days after seeding. The results were obtained at two different sites- Besor and Hazeva, both with sandy soils. Ri is the ratio of seasonal overall irrigation to evaporation from a class A pan (*Source*: Bar-Yosef *et al.*, 1992).

The required steady state nutrient concentration in the soil that is expected to be maintained when supply equals optimal uptake rate by the plants, is determined by the pre-seeding basic (usually broadcast) fertilization. To fertilize properly, one must know the relationship between application rate and nutrient availability to plants on the one hand, and between fertilizer dose and nutrient concentration in the soil solution on the other hand. Despite the importance of basic fertilization in creating the background nutrient concentrations in the field, it will not be discussed further in this review.

8.2.2.3. Selecting fertilizers for fertigation

The data in Tables 14, 15 and 16 show the minimal application rates of N, P and K that must be added to the soil via the water at any growth stage to satisfy plant demand. The question arises as to what is the recommended fertilizer to be used for this purpose, and how various conditions in the system affect the decision regarding which fertilizer to choose.

Fertigation under saline conditions

A 10 meq/L solution has an electrical conductivity (EC) of ~1 dS/m and an osmotic pressure of approximately 0.30 bar (25°C). According to the US Salinity Laboratory (1954), irrigation water with an EC exceeding 1.44 and 2.88 dS/m constitutes a moderate and a high salinization hazard, respectively. According to Tables 14 and 16, and assuming a daily irrigation of 5 mm (50 m^3 ha^{-1}), nitrogen and potassium concentrations in the irrigation water at the time of maximum consumption rate may reach values of 15 to 20 meq/L, which correspond to an EC of 1.5-2.0 dS/m. Under such conditions, and especially where the water EC>1, which is common in arid zones, care should be taken to minimize the amount of accompanying ions added with the N or K. For example, KCl, which is a cheap source of K, should be replaced by KNO_3 and K_2HPO_4, while NH_4NO_3 and urea should be preferred over $(NH_4)_2SO_4$.

Sodium-based fertilizers (e.g. $NaNO_3$ or NaH_2PO_4) are unsuitable sources due to the adverse effect of Na on soil hydraulic conductivity (Bresler *et al.*, 1982) and on plant functioning (Mengel and Kirkby, 1987).

Fertigation solution pH

Different sources of N fertilizers have different effects on irrigation water and soil pH. High pH values (>7.5) in the irrigation water are undesirable, because Ca and Mg carbonate and orthophosphate precipitations may occur in the tubes and drippers. High soil pH may reduce Zn, Fe and P availability to plants. Consequently, it is not recommended to use ammonia in fertigation, since it raises the pH when injected into irrigation water. Compounds which may reduce the irrigation water pH are nitric (NHO_3) and orthophosphoric (H_3PO_4) acids. Depending on their price, these sources may be used to reduce the irrigation water pH down to 5. Lower pH values are detrimental to root membranes and may increase the Al and Mn concentrations in the soil solution to toxic levels.

Another factor which affects soil pH, especially at the soil-root interface, is the NH_4-to-NO_3 ratio in the irrigation water. When NH_4 uptake is predominant, H^+ is being excreted from roots. When NO_3 is the major ion absorbed, OH^- is released into the soil (Mengel and Kirkby, 1987). Fluctuations in soil pH around the roots of the order of $\pm$ 1.5 pH units due to NH_4-N or NO_3-N supply were reported in the literature (Barber, 1984). In tomato and roses, a stable pH in nutrient solution was maintained when the NH_4-to-NO_3 molar ratio in the solution was between 1:4 and 1:3 (Feigin *et al.*, 1979, 1986). Muskmelon which was grown in rockwool with NH_4 as the sole source of N decreased the leachate pH from ~7 in the inflowing solution to

~4 (Bar-Yosef *et al.*, 1995). According to Ganmore-Neumann and Kafkafi (1980, 1983), NH_4-N is an undesirable source of nitrogen for tomato and strawberry plants at root-zone temperatures above 30°C, because it is detrimental to root growth and development.

Nutrient mobility in soils

Spatial distribution of nitrogen in soil is strongly affected by the source of N added via the irrigation water. Ammonium is adsorbed by soil colloids and metal oxides and thus has a restricted mobility relative to the unadsorbed NO_3^-. Ammonium is nitrified in soil to NO_3 by microbial mediated reactions, at a rate which depends on soil temperature and moisture content. The half-life of this process at 25°C and field capacity moisture content is about 2 weeks (Stanford and Epstein, 1974). In cases of temporary N application rates in excess of plant consumption, it is advisable to apply the excess amount as NH_4-N, and thus avoid rapid leaching of the unexploited N outside the root zone.

Urea is a highly soluble, chargeless molecule, which easily moves with the irrigation water and is distributed in the soil similarly to NO_3^-. At 25°C, it is hydrolyzed by soil microbial enzymes into NH_4 within a few days. This hydrolysis results in an increase in soil pH, which in soils of pH>7.5 may reduce P availability to plants.

Phosphorus mobility in soil is very restricted due to its strong retention by soil oxides and clay minerals. Continuous application of orthophosphate through the irrigation water was shown to be superior to applying P at adequate quantities as basic fertilization (Bar-Yosef *et al.*, 1989). This stemmed from the fact that both P adsorption and P crystallization, which reduce P concentration in the soil solution and thus decrease P uptake rate by plants and P migration distance in the soil, are time-dependent reactions. The half-life of these reactions is roughly a few hours and several weeks, respectively. Due to the frequent P application via the water, the residence time of P in the soil was reduced appreciably, and P concentration in the soil solution between successive fertigations was considerably higher than expected from adsorption and precipitation equilibrium considerations.

When choosing the P fertilizer for fertigation, care must be taken to avoid P-Ca and P-Mg precipitation in the tubes and emitters (Bar-Yosef and Imas, 1995). From this standpoint, acid P fertilizers (e.g. phosphoric acid or monoammonium phosphate) are recommended, because the monovalent ($H_2PO_4^-$)-Ca and Mg salts are far more soluble than the HPO_4^{2-} Ca and Mg salts.

Ready-mix fertilizers

Commercial ready-mix fertilizers (in solid or liquid form) are characterized by their nutrient contents, elements weight ratio, and specific chemicals constituting the fertilizer. The combined data in Tables 5, 6 and 7 may help to define the N, P, K weight ratio of a given compound fertilizer designed to supply these elements to a given crop during a certain growth period. The compounds constituting a ready-mix fertilizer (source of N and accompanying ions) should be evaluated based on the principles discussed in preceding sections.

8.2.3. Monitoring the plant-soil system

The principles outlined in section 2 allow one to fertilize during the growing season in order to sustain optimum crop growth and yield. The optimal consumption rates by plants as shown in Tables 5, 6 and 7 are the product of optimal dry matter production (ODM) times optimum nutrient concentration in plant tissues (ONC). Both functions are available but not presented in this review. By monitoring plant dry weight and nutrient concentrations therein, and comparing the data with the ODM and ONC at critical growth stages, one can determine whether the crop is developing and absorbing nutrients according to the required rates. Any deviation from the ODM and ONP values must be followed by correction of the nutrient and water supply rates, so that conditions in the soil will conform with the required concentrations.

The required nutrient concentrations in the soil solution which facilitate optimal consumption rate by plants can be estimated according to the preceeding guidelines. By means of soil tests, the deviation between prevailing and optimum concentrations can be determined, and correction measures to restore the required concentrations in the soil can be undertaken.

The soil water content (θ) must be maintained at a level that will not limit water and nutrient movement to the roots. Discussion of the principles of irrigation management (rates and timing), showing how to determine the required θ, or matric potential ($\o$) in a given soil, and how to obtain and maintain it there, are outside the scope of this work. For supplementary information on this subject, the reader is refered to reviews by Bucks *et al.* (1982) and Dasberg and Bresler (1985). To ensure that water will not become an uptake-limiting factor on the one hand, and will not cause anaerobic conditions due to over-irrigation on the other hand, soil θ, or $\o$, must be monitored periodically. Soil matric potential is being monitored under field conditions by tensiometers, and θ by neutrone probes (Gardner,

1986) or TDR (time domain reflectometry, Topp and Davis, 1985). Under trickle irrigation, the recommended ø should be between -8 and -15 cbar in sandy soils and between -10 and -30 cbar in clay soils.

Where possible, nutrient concentrations in the soil solution should also be monitored in order to ensure that they are within the required concentration range. This can be done by either of two approaches. The first approach involves soil sampling at one or more reference positions in the root zone as a function of time, and extraction to determine soluble and sorbed nutrient concentrations in the soil. The second approach is to sample the soil solution directly by means of vacuum cups inserted permanently in the soil, and analyze the collected solution for various nutrient concentrations in it. The convenient operation and low price of the vacuum cup system have made it very popular with farmers. The most commonly used vacuum cup is constructed of porous ceramics and is described in detail by Rhoades and Oster (1986).

None of the above mentioned methods gives the true nutrient concentration in the soil or soil solution. However, the results obtained are closely correlated with the real concentrations, and hence can show variations in nutrient status in soil (depletion or accumulation trends) over time.

8.2.4. Concluding remarks

There have been significant advances in trickle irrigation and fertilization equipment, automation and maintenance devices within the past decade. Efficient utilization of this equipment is hampered by gaps in our knowledge regarding optimum consumption rate of various nutrients by crops as a function of time, concentration-flux of uptake relationships, and lack of accurate, reliable and rapid monitoring devices in the soil-plant system. In this work, the available biological data pertinent to vegetable fertigation during the season have been presented. Guidelines for rational use of different fertilizers through the water have been proposed, and ways to estimate required nutrient concentrations in the soil solution to obtain predefined optimal uptake rates have been discussed. The biological data base presented in this work is still very limited, and cannot be simply extrapolated to different climatic conditions. It should be regarded, however, as an example of the type of information needed to gain full benefit from sophisticated fertigation systems.

Drip fertigation strongly affects plant root volumes. More research is needed to clarify soil physical and chemical effects on root growth, uptake and excretion. An enhanced understanding of these phenomena will help us in using drip fertigation to produce desired root systems, and thus obtain plants more efficient in utilizing nutrients and water from the soil. It will also help to design drip fertigation systems based on root characteristics, as well as soil hydraulic properties, as planning parameters.

Monitoring should be advanced on two fronts: (i) Development of reliable standard curves defining the optimal dry matter production rate, nutrient concentrations, and water status in plants as a function of time, over a wide range of growth conditions. Nutrient status, or related parameters (e.g. nitrate in petioles) should be determined by the growers themselves to achieve a short response time in correcting observed deviations between current and standard curve results. (ii) Improving the methodology of determining water status in soil and nutrient concentrations in the soil solution. These monitoring tests should also be done by the farmers in the field, so that correction measures based on the obtained results will be effective.

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References (Chapters 1 to 8.1)

Alt, D. (1984): Langjähriger Feldversuch zur P-, K-, und Mg-Düngung von Gemüsekulturen. Gartenbauwissenschaft 49, 270-279.

Anon. (1985): Arbeitskalender für das Freiland. Gemüse 6/1985, 288-293.

Anon. (1984): Bemestingsadviesbasis intensieve vollegrondsgroenteteelt. Consulentschap voor bodem- water- en bemestingszaken in de akkerbouw en tuinbouw, Wageningen, The Netherlands.

Archer, J. (1988): Crop nutrition and fertilizer use. Farming Press, Ipswich, UK.

AVRDC (1985): Effect of time, form, and concentration of nitrogen application on Chinese cabbage tipburn. Progress Report, Asian Vegetable Research and Development Center, 385-393. Tainan, Taiwan.

Balvoll, G. (1989): Grønsakdyrking på friland. 4th ed. Landbruksforlaget, Oslo.

Barber, S.A. (1962): A diffusion and mass flow concept of soil nutrient availability. Soil Science 93, 39-49.

Barker, A.V. and Mills, H.A. (1980): Ammonium and nitrate nutrition of horticultural crops. Hortic. Reviews 2, 395-423.
Barker, A.V. (1989): Genotypic responses of vegetable crops to nitrogen nutrition. Hort. Science 24, 584-591.
Barley, K.P. (1970): The configuration of the root system in relation to nutrient uptake. Advances in Agronomy 22, 159-201.
Batra, B.R. and Kalloo (1990): Effect of different levels of irrigation and fertilization on growth and yield of carrot (*Daucus carota* L.) for root production. Vegetable Science 17, 127-139.
BDH (1984): The snappy sap test - its use with vegetable crops. BDH Ltd., Poole, UK.
Berard, L.S. (1990): Effects of nitrogen fertilization on stored cabbage. I: Development of physiological disorders on tolerant and susceptible cultivars. J. Hort. Sci. 65, 289-296.
Bergmann, W. and Neubert, P. (1983): Pflanzendiagnose und Pflanzenanalyse. Fischer Verlag, Jena, DDR.
Beringer, H. and Trolldenier, G. (1978): Influence of K nutrition on the response to environmental stress. *In*: Potassium research - Review and trends. International Potash Institute, Bern.
Bierhuizen, J.F., Ebbens, J.L. and Kooman, N.C.A. (1973): Effects of temperature and radiation on lettuce growing. Netherlands Journal of Agricultural Science 21, 110-116.
Böhmer, M. (1980): Der Mineralstickstoffgehalt von Böden mit Feldgemüsebau und seine Bedeutung für die Stickstofferernährung der Pflanze. Doctoral Thesis, Horticulture Faculty, Univ. Hanover, FRG.
Bould, C. (1983): Methods of diagnosing nutrient disorders in plants. *In*: Diagnosis of mineral disorders in plants. Vol. 1: Principles. H.M.S.O., London.
Brewster, J.L. (1990): *In*: Onions and allied crops. Vol. 1, Botany, Physiology, and Genetics. Eds. H.D. Rabinowitch and J.L. Brewster. CRC Press, Boca Raton, Florida, USA.
Brown, J.C. (1978): Mechanism of iron uptake by plants. Plant, Cell and Environment 1, 249-257.
Bunt, A.C. (1976): Modern potting composts. George Allen and Unwin, London.
Burghardt, H. and Ellering, K. (1986): Verträglichkeit und Wirkung von Blattdüngungsmassnahmen bei Gemüsekulturen. Gartenbauwissenschaft 51, 58-62.
Burns, I.G. (1974): A model for predicting the redistribution of salts applied to fallow soils after excess rainfall or evaporation. J. Soil Science 25, 165-178.

Burns, I.G. (1990): The effects of continuity of early nitrogen nutrition on growth and development of *Lactuca sativa*. *In*: Plant nutrition - physiology and applications; Ed. M.L. van Beusichem. Kluwer Academic Publishers, The Netherlands.

Bussler, W. (1958): Manganvergiftung bei höheren Pflanzen. Z. Pflanzenernährung Düngung 81, 256-265.

Carolus, R.L. (1936): Experiences with rapid chemical tests for the determination of nutrient deficiencies in vegetable crops. Proc. Amer. Soc. Hort. Sci. 33, 579-83.

Chapman, H.D. (1966): Diagnostic criteria for plants and soils. Univ. California Div. of Agric. Sciences.

Claasen, N. (1992): Nutrient acquisition and soil-plant interactions. Proc. 2nd ESA Congress, Warwick Univ. (Ed. A. Scaife), 218-227.

Clarkson, D.T. and Hanson, J.B. (1980): The mineral nutrition of higher plants. Annual Review of Plant Physiology 31, 239-298.

Clement, C.R., Hopper, M.J. and Jones, L.H.P. (1978): The uptake of nitrate by *Lolium perenne* from flowing nutrient solution. Journal of Experimental Botany 29, 453-464.

Collier, G.F. and Tibbits, T.W. (1982): Tipburn of lettuce. Horticultural Reviews 4, 49-65.

Cooke, G.W., Jackson, M.V., Widdowson, F.V. and Wilcox, J.C. (1956): Fertilizer placement for horticultural crops. Journal of Agricultural Science, Cambridge 47, 249-256.

Costigan, P.A. (1985): A survey of nutrient concentrations and early shoot and root growth of drilled lettuce in twenty-one commercial sowings in one year. J. Hort. Sci. 60, 233-243.

Costigan, P.A. (1988): The placement of starter fertilizer to improve the early growth of drilled and transplanted vegetables. Proc. Fertilizer Society No. 274, 24 pp. The Fertilizer Society, London.

Cummings, G.A. and Wilcox, G.E. (1968): Effect of potassium on quality factors - fruits and vegetables. *In*: The role of potassium in agriculture. American Society of Agronomy, Madison, Wisconsin, USA, 243-267.

Espinoza, L., Sanchez, C.A. and Schueneman (1993): Celery yield responds to phosphorus rate but not phosphorus placement on histosols. Hort. Sci. 28, 1168-1170.

Everaats, A.P. (1993): Strategies to improve the efficiency of nitrogen fertilizer use in the cultivation of *brassica* vegetables. Acta Hort. 339, 149-160.

Farrer, K., Caldwell, T.H. and Archer, F. (1976): Trace element deficiencies in crops. ADAS Advisory paper No. 17. MAFF, Pinner, UK.

Fenn, L.B. and Miyamoto, S. (1981): Ammonia loss and associated reactions of urea in calcareous soils. Soil Sci. Soc. Am. J. 45, 537-540.
Fenwick, G.R., Griffiths, N.M. and Heaney, R.K. (1983): Bitterness in Brussels sprouts (*Brassica oleracea* L. var. *Gemmifera*). The role of glucosinolates and their breakdown products. J. Sci. Food and Agric. 34, 73-80.
Fink, N. and Scharpf, H.C. (1993): N-Expert - A decision support system for vegetable fertilization in the field. Acta Hort. 339, 67-74.
Fischer, J. (1992): The influence of different nitrogen and potassium fertilizers on the chemical flavour composition of kohlrabi (*Brassica oleracea* var. *gongylodes* L.). J. Sci. Food. and Agric. 60, 465-470.
Föhse, D., Claasen, N. and Jungk, A. (1988): Phosphorus efficiency of plants. I. External and internal P requirement and P uptake efficiency of different plant species. Plant and Soil 110, 101-109.
Föhse, D., Claasen, N. and Jungk, A. (1991): Phosphorus efficiency of plants. II. Significance of root radius, root hairs and cation-anion balance for phosphorus influx in seven plant species. Plant and Soil 132, 261-262.
Follett, R.H., Murphy, L.S. and Donahue, R.L. (1981): Fertilizers and soil amendments. Prentice-Hall, New Jersey, USA.
Forman, D., Al-Dabbagh, S. and Doll, R. (1985): Nitrates, nitrites and gastric cancer in Great Britain. Nature 313, 620-625.
Freeman, G.G. and Mossadeghi, N. (1970): Effect of sulphate nutrition on flavour components of onion (*Allium cepa*). J. Sci. Food and Agric. 21, 610-615.
Freeman, G.G. and Mossadeghi, N. (1972): Influence of sulphate nutrition on flavour components of three cruciferous plants: radish (*Raphanus sativus*), cabbage (*Brassica oleracea capitata*) and white mustard (*sinapis alba*). J. Sci. Food and Agric. 23, 387-402.
Gardner, B.R. and Roth, R.L. (1989): Plant analysis for nitrogen fertilization of asparagus. J. Am. Soc. Hort. Sci. 114, 741-745.
Geraldson, C.M. (1954): The control of blackheart in celery. Proc. Am. Soc. Hort. Sci. 63, 353-358.
Gooding, M.J. and Davies, W.P. (1992): Foliar urea fertilization of cereals: a review. Fert. Res. 32, 209-222.
Graham, R.D. and Webb, M.J. (1991): Micronutrients and disease resistance and tolerance in plants. *In*: Micronutrients in agriculture. 2nd Ed. Soil Sci. Soc. Am., Madison, Wisconsin, USA, 329-370.
Greenwood, D.J., Cleaver, T.J. and Turner, M.T. (1974a): Fertilizer requirements of vegetable crops. Proc. Fert. Soc. No. 145. The Fertilizer Society, London.

Greenwood, D.J., Wood, J.T. and Cleaver, T.J. (1974b): A dynamic model for the effects of soil and weather conditions on nitrogen response. J. Agric. Sci., Cambridge 82, 455-467.

Greenwood, D.J., Cleaver, T.J., Loquens, S.M.H. and Niendorf, K.B. (1977): Relationship between plant weight and growing period for vegetable crops grown in the United Kingdom. Ann. Bot. 41, 987-997.

Greenwood, D.J., Barnes, A. and Cleaver, T.J. (1978): Measurement and prediction of the changes in protein contents of field crops during growth. J. Agric. Sci., Cambridge 91, 467-477.

Greenwood, D.J., Cleaver, T.J., Turner, M.K., Hunt, J., Niendorf, K.B. and Loquens, S.M.J. (1980a): Comparison of the effects of potassium fertilizer on the yield, potassium content and quality of 22 different vegetable and agricultural crops. J. Agric. Sci., Cambridge 95, 441-456.

Greenwood, D.J. *et al.* (1980b): ibid. 95, 457-469.

Greenwood, D.J., Kubo, K., Burns, I.G. and Draycott, A. (1989): Apparent recovery of fertilizer N by vegetable crops. Soil Sci. & Plant Nutr. 35, 367-381.

Gysi, Ch. (1993): Nährstoffbilanz im Gesamtbetrieb. Flugschrift Nr. 127. Eidg. Forschungsanstalt für Obst-, Wein- und Gartenbau, Wädenswil, Switzerland.

Gysi, Ch., Ryser, J.P., Matthäus, D. and Koch, W. (1993): *In*: Richtlinien für den Schweizerischen Gemüsebau. Schweiz. Gemüse-Union, Ins, Switzerland.

Hahn, E. (1985): Bormangel bei Gemüse. Nachrichtenblatt für den Pflanzenschutz in der DDR, 39, 206-209.

Hansen, S., Jensen, H.E., Nielsen, N.E. and Svendsen, H. (1993): The soil plant system model DAISY. Jordbrugsforlaget, Copenhagen.

Haynes, R.J. (1984): Lime and phosphate in the soil-plant system. Adv. Agron. 37, 249-315.

He Tianxu, He Chengdu and Härdter, R. (1994): The effects of K and Mg fertilizers applied to cabbage on yield, quality and economic returns. Potash Review No. 2, 1994, 1-5.

Hewitt, E.J. (1983): The effects of mineral deficiencies and excesses on growth and composition. *In*: Diagnosis of mineral disorders in plants. Vol. 1: Principles. H.M.S.O., London.

Hinton, L. (1991): The European market for fruit and vegetables. Elsevier, London.

Hole, C.C. and Scaife, A. (1993): An analysis of the growth response of carrot seedlings to deficiency in some mineral nutrients. Plant and Soil 150, 147-156.

Huber, D.M. and Watson, R.D. (1974): Nitrogen form and plant disease. Annual review of Phytopathology 12, 139-165.

Ikeda, H. (1988): Studies on the utilization of nitrogen by vegetable crops with special reference to the form of nitrogen supplied. Bull. Univ. Osaka Prefecture 40, 69-117.

IPI (1976): Fertilizer use and plant health. International Potash Inst., Bern.

Jenkinson, D.S., Fox, R.H. and Rayner, J.H. (1985): Interactions between fertilizer nitrogen and soil nitrogen - the so-called "priming" effect. J. Soil Sci. 36, 425-444.

Jones, F.G.W. (1976): see IPI (1976), p. 233.

Keipert, K., Wedler, A. and Overbeck, G. (1990): Alternative cultivation of apples and vegetables. Schriftenreihe der Landwirtschaftskammer Rheinland No. 66.

Khasawneh, F.E. and Doll, E.C. (1978): The use of phosphate rock for direct application to soils. Adv. Agr. 30, 159-206.

Király, Z. (1976): see IPI (1976), p. 33.

Kolota, E. (1984): Effect of fertilization methods and nitrogen form on vegetable yields with and without irrigation. Biuletyn Warzynwniczy 27. Whitehead cabbage 203-235; Beet roots 237-260; Leeks 261-282.

Kramer, P. (1949): Plant and soil water relationships. McGraw-Hill, New York.

Krikun, J., Haas, J.H., Dodd, J. and Kinsbursky, R. (1990): Myccorhizal dependence of four crops in a P-absorbing soil. Plant and Soil 122, 213-217.

Lagatu, H. and Maume, L. (1924): Etude, par l'analyse périodique des feuilles, de l'influence des engrais de chaux, de magnésie, et de potasse sur la vigne. Comptes rendus de l'Académie des Sciences 179, 932-934.

Leuchs, F. (1959): Über Beziehungen zwischen Fäulniserscheinungen, Wundheilung und Kaliversorgung an Rosenkohl. Zeitschrift für Pflanzenkrankheiten und Pflanzenschutz 66, 499-508.

Lindsay, W.L. (1972): Zinc in soils and plant nutrition. Advances in Agronomy 24, 147-186.

Lingle, J.C. and Holmberg, D.M. (1957): The response of sweet corn to foliar and soil zinc on a zinc deficient soil. Proc. Am. Soc. Hort. Sci. 70, 308-315.

Locascio, S.J. (1987): Progress in nutrition of Florida vegetables during the past 100 years. Proc. Fla. State Hort. Soc. 100, 398-405.

Locascio, S.J. and Fiskell, J.G.A. (1987): Vegetables needs for micronutrients in perspective. Soil and Crop Sci. Soc. of Florida Proc. 47, 12-18.

Lorenz, O.A. and Maynard, D.N. (1988): Knott's Handbook for Vegetable Growers. 3rd Ed. John Wiley & Sons, New York.

Lorenz, O.A., Weir, B.L. and Bishop, J.C. (1972): Effect of controlled-release nitrogen fertilizers on yield and nitrogen absorption by potatoes, cantaloupes, and tomatoes. J. Am. Soc. Hort. Sci. 97, 334-337.

Lorenz, H.P., Schlaghecken, J. and Engl, G. (1989): Gezielte Stickstoff-Versorgung im Gemüsebau nach dem "Kulturbegleitenden N_{min} Sollwerte (KNS)-System". Neustadter Hefte No. 26. LLFLWG, Neustadt an der Weinstraße, FRG.

Lucas, R.E. (1968): Potassium nutrition of vegetable crops. *In*: The role of potassium in agriculture. American Society of Agronomy, Madison, Wisconsin, USA, 489-498.

MacNicol, R.D. and Beckett, P.H.T. (1985): Critical tissue concentrations of potentially toxic elements. Plant and Soil 85, 107-129.

MAFF (1994): Fertilizer recommendations for agricultural and horticultural crops (RB209). 6th Ed. MAFF, London.

Marschner, H. (1986): Mineral nutrition in higher plants. Academic Press, London.

Mattusch, P. (1978): Ein Beitrag zur Verminderung der durch den Kohlhernieerreger *Plasmodiophora brassicae* verursachten Schäden durch den Einsatz von Kalkstickstoff. Nachrichtenblatt Deutscher Pflanzenschutzdienst (Braunschweig) 30, S, 150-152.

Mayer, C., Venter, F. and Dehne, H.W. (1989): Zur Bedeutung der vesikular-arbuskularen Mykorrhiza für die Kultur von Gemüsejungpflanzen. Bodenkultur 40, 37-45.

Maynard, D.N. (undated): Calcium deficiency disorders in vegetable crops. *In*: A guide to the uses of calcium nitrate for crop production. Wilson & Geo. Meyer, San Francisco.

Maynard, D.N., Barker, A.V., Minotti, P.L. and Peck, N.H. (1976): Nitrate accumulation in vegetables. Adv. Agron. 28, 71-118.

Maynard, D.N. and Barker, A.V. (1972): Internal browning of Brussels sprouts: a calcium deficiency disorder. J. Am. Soc. Hort. Sci. 97, 789-792.

Maynard, D.N. and Locascio, S.J. (1982): Nutrition of vegetable crops in Florida, USA. Proc. 21st International Horticultural Congress, Hamburg, FRG, Vol. 2, 710-725.

Maynard, D.N. and Lorenz, O.A. (1979): Controlled-release fertilizers for horticultural crops. Hort. Review 1, 79-140.

Mengel, K. and Kirkby, E.A. (1987): Principles of plant nutrition. International Potash Institute, Bern.

Miller, E.V., Army, T.J. and Krackenberger, H.T. (1956): Ascorbic acid, carotene, riboflavin and thiamine contents of turnip greens in relation to nitrogen fertilization. Soil Sci. Soc. Am. Proc. 20, 379-382.

Milthorpe, F.L. and Moorby, J. (1974): An introduction to crop physiology. Cambridge University Press, Cambridge, UK.

Mitscherlich, E.A. (1909): Das Gesetz des Minimums und das Gesetz des abnehmenden Bodenertrages. Landwirtschaftliches Jahrbuch 38, 537-52.

Mitscherlich, E.A. (1928): Die zweite Annäherung des Gesetzes der Effekte der Wachstumsfaktoren. Zeitschrift für Pflanzenernährung A12, 273.

Neeteson, J.J. (1985): Effectiveness of the assessment of nitrogen fertilizer requirement for potatoes on the basis of soil mineral nitrogen. *In*: Assessment of nitrogen fertilizer requirement. Eds: Neeteson, J.J. and Dilz, K. Inst. for Soil Fertility, Haren, The Netherlands.

Nitsch, A. (1984): Mit Teststäbchen und Reflektometer. Hannoversche Land- und Forstwirtschaftliche Zeitung 39.

Nitsch, A. and Varis, E. (1991): Nitrate estimates using the Nitrachek test for precise N-fertilization during plant growth and, after harvest, for quality testing potato tubers. Potato Research 34, 95-105.

NVRS (1980): The NPK Predictor. National Vegetable Research Station, Wellesbourne, CV35 9EF, UK.

Olsen, C. (1950): The significance of concentration for the rate of ion absorption by higher plants in water culture. Physiologia Plantarum 3, 152-164.

Page, E.R. (1972): Ammonia as a fertilizer for vegetables. Reports on the Progress of Applied Chemistry 56, 448-455.

Page, E.R., Tatham, P.B. and Wood, M.B. (1974): Aqueous ammonia as a nitrogen fertilizer for single harvested Brussels sprouts. Exp. Hort. 26, 82-90.

Page, E.R. and Cleaver, T.J. (1983): Effects of nitrogen fertilizers on the emergence of vegetable seedlings. J. Sci. Food and Agric. 34, 13-22.

Peck, N.H., Cantliffe, D.J., Shallenberger, R.S. and Bourke, J.B. (1974): Table Beet (*Beta vulgaris* L.) and nitrogen. Search Agric. 4, 1-25.

Peck, N.H. and MacDonald, G.E. (1975): Plant response to concentrated superphosphate and potassium chloride salts. VI. Sweet Corn (*Zea mays* L. var. *rugosa*). Search Agric. 5, 1-35.

Peck, N.H. and Stamer, J.R. (1970): Plant response to concentrated superphosphate and potassium chloride fertilizers: III. Cabbage (*Brassica oleracea*). New York Agric. Exp. Stn. Bull. 830.

Penman, H.L. (1948): Natural evaporation from open water, bare soil, and grass. Proceedings of the Royal Society, London; Series A, 193, 120.

Perrenoud, S. (1990): Potassium and plant health. 2nd Ed. International Potash Institute, Bern.

Plant, W. (1956): The effects of molybdenum deficiency and mineral toxicities on crops on acid soil. J. Hort. Sci. 31, 163-176.

Prasad, R., Rajale, G.B. and Lakhdive, B.A. (1971): Nitrification retarders and slow-release nitrogen fertilizers. Adv. Agron. 23, 337-383.

Purvis, E.R. and Carolus, R.L. (1964): Nutrient deficiencies in vegetable crops. *In*: Hunger signs in crops. 3rd Ed. (H.B. Sprague, Ed.). David McKay, New York.

Rahn, C.R., Vaidyanathan, L.V. and Paterson, C.D. (1992): Improving the prediction of nitrogen for *brassica* crops. Proc. 2nd ESA Congress, Warwick Univ. (Ed. A. Scaife), 424-425.

Randall, G.W. and Hoeft, R.G. (1988): Placement methods for improved efficiency of P and K fertilizers: a review. J. Prod. Agric. 1, 70-79.

Rao, J.K., Sahrawat, K.L. and Burford, J.R. (1987): Diagnosis of iron deficiency in groundnut, *Arachis hypogea* L. Plant and Soil 97, 353-359.

Reuter, D.J. and Robinson, J.B. (1986): Plant analysis: An interpretation manual. Inkata Press, Melbourne.

Roll-Hansen, J. (1974): Fertilizer experiments with carrots on peat soil. Forskning Og Forsoki Landbruket 25, 201-218.

Sanchez, C.A., Burdine, H.W., Guzman, V.L. and Beverly, R.B. (1989): Management of high pH histosols for lettuce production. Proc. Florida State Hort. Soc. 102, 341-343.

Scaife, M.A. (1968): Maize experiments in Western Tanzania. J. Agric. Sci., Cambridge 70, 209-222.

Scaife, M.A. (1974): Computer simulation of nitrogen uptake and growth. Plant Analysis and Fertilizer Problems. Proc. 7th Intern. Coll., Hanover, FRG, 413-425.

Scaife, A. and Turner, M.K. (1983): Diagnosis of mineral disorders in vegetables. Vol. 2. Vegetables. H.M.S.O., London.

Scaife, A. and Turner, M.K. (1985): Effect of nitrogen top-dressing on Brussels sprout flavour. Tests of Agrochemicals and Cultivars 106, 172-173.

Scaife, A. and Wurr, D.C.E. (1990): Effects of nitrogen and irrigation on hollow stem of cauliflower (*Brassica oleracea* var. *Botrytis*). J. Hort. Sci. 65, 25-29.

Scaife, M.A. and Barnes, A. (1977): The relationship between crop yield and petiole nitrate concentration at various growth stages. Plant and Soil 46, 705-712.

Scaife, M.A. and Bray, B.G. (1977): Quick sap tests for improved control of crop nutrient status. ADAS Quarterly Review 27, 137-145.

Scaife, A., Saraiva Ferreira, M.E. and Turner, M.K. (1986): Effect of nitrogen form on the growth and nitrate concentration of lettuce. Plant and Soil 94, 3-16.

Scaife, A. and Turner, M.K. (1987): Field measurements of sap and soil nitrate to predict nitrogen top-dressing requirements of Brussels sprouts. J. Plant Nutr. 10, 1705-1712.

Scaife, A. and Turner, M.K. (1984): Use of Merckoquant nitrate test strips for optimization of vegetable nitrogen nutrition. Proc. 6th Intern. Coll. for the optimization of plant nutrition, Montpellier, France. Vol. 2, 617-624.

Scharpf, H.C. (1991): Stickstoffdüngung im Gemüsebau. AID, Bonn, FRG.

Scharpf, H.C. and Weier, U. (1988): Abgestimmte Sollwerte für Stickstoffdüngung im Gemüsebau. *In*: "Die industrielle Obst- und Gemüseverwertung", No. 4/1988.

Schrage, R. (1990): Methoden zur Bestimmung des Stickstoff-Düngerbedarfs von Gemüsekulturen mit geringem analytischen Aufwand. Doctoral Thesis, Hort. Fac., Univ. Hanover.

Shallenberger, R.H. and Moyer, J.C. (1958): Relationships between pyrrolidonecarboxylic acid and an off-flavor in beet puree. Agric. Fd. Chem. 6, 604-606.

Sharpley, A.N. and Menzel, R.G. (1987): The impact of soil and fertilizer phosphorus on the environment. Adv. Agron. 41, 297-324.

Shorrocks, V.M. and Alloway, B.J. (undated): Copper in plant, animal, and human nutrition. Copper Dev. Assoc., Potters Bar, UK.

Shorrocks, V.M. (undated): Boron deficiency: its prevention and cure. Borax Holdings Ltd., London.

Sieling, E.R.M. (1992): Stikstofbemestingsrichtlijnen voor de akkerbouw en de groenteteelt in de vollegrond. Informatie en Kennis Centrum voor de Akkerbouw en de Groenteteelt in de vollegrond, Lelystad, The Netherlands.

Sommer, K. (1991): Stickstoffversorgung von Gemüsepflanzen auf Ammonia-Basis unter besonderer Berücksichtigung der Jungpflanzenanzucht. Agrikulturchemisches Institut der Rheinischen Friedrich-Wilhelm-Universität Bonn.

Soorsma, H.E. (1992): Het stikstofbijmestsysteem voor vollegrongsgroenten: inzicht in bemesting. Meststoffen 1992, 16-20.

Sørensen, J.N. (1993): Use of the N_{min} method for optimization of vegetable nitrogen nutrition. Acta Hort. 339, 179-192.

Sprague, H.B. (Ed.) (1964): Hunger signs in crops. 3rd Ed. David McKay, New York.

Stone, D.A. and Rowse, H.R. (1992): Reducing the nitrogen requirement of vegetable crops by precision fertilizer injection. Aspects of Applied Biology 30, 399-402.

Terman, G.L. (1979): Volatilization losses of nitrogen as ammonia from surface-applied fertilizers, organic amendments, and crop residues. Adv. Agron. 31, 189-223.

Thorne, W. (1957): Zinc deficiency and its control. Adv. Agron. 9, 31-65.

Truog, E., Berger, K.C. and Attoe, O.J. (1953): Responses of nine economic plants to fertilization with sodium. Soil Sci. 76, 41-50.

Tsai-fua Chiu (1975): Calcium mobility studies in plants with particular reference to nutritional disorders. Ph.D. Thesis, Univ. Bristol, U.K.

Van der Paauw, F. (1971): An effective water extraction method for the determination of plant-available soil phosphorus. Plant and Soil 34, 467-481.

Venter, F. (1984): Nitrate contents of head lettuce as influenced by nitrificides. Acta Hort. 163, 231-236.

Vesanto, T. and Lehtimäki, S. (1993): Horticulture in Finland. Agric. Economic Res. Inst. Research Publications No. 71.

Vogtmann, H., Matthies, K., Kehres, B. and Meier-Ploeger, A. (1992): Enhanced food quality induced by compost applications. Proc. Intern. Composting Res. Symp., Columbus, Ohio, USA; March 27, 1992.

Wallace, T. (1961): The diagnosis of mineral deficiencies in plants by visual symptoms. H.M.S.O., London.

Wedler, A. (1985): Einfluss der Düngung auf die Qualität von Gemüse. Deutscher Gartenbau 39, 642-644.

Williams, D.E. (1961): The absorption of potassium as influenced by its concentration in the nutrient medium. Plant and Soil 15, 387-399.

Wright, J. (1994): A decade of field vegetables. The Horticulturalist 3, 8-12.

Yadav, B.R. and Tomar, S.P.S. (1990): Comparative effect of chloride and sulphate salinity in irrigation water on yield and mineral nutrition of cauliflower (*Brassica oleracea* var. *Botrytis*). Vegetable Sci. 17, 191-194.

Zehler, E., Kreipe, H. and Gething, P. (1981): Potassium sulphate and potassium chloride. Their influence on yield and quality of cultivated plants. IPI-Research Topics No. 9. International Potash Institute, Bern.

Zinc in Crop Nutrition (undated): International Lead Zinc Organization, Inc., New York.

References (Chapter 8.2)

Barber, S.A. (1984): Soil Nutrient Bioavailability. Wiley-Interscience. New York.

Bar-Tal, A., Bar-Yosef, B. and Kafkafi, U. (1990): Pepper transplant response to root volume and nutrition in the nursery. Agron. J. 82: 989-995.

Bar-Tal, A., Pressman, E. and Rylska, E. (1994): Tomato response to K-Ca ratios and root restriction in solution culture. Annual report submitted to CALAR tri-national (Egypt, US, Israel) project.

Bar-Yosef, B. (1971): Fluxes of P and Ca into intact corn roots and their dependence on solution concentration and root age. Pl. Soil 35: 589-600.

Bar-Yosef, B., Kramer, S. and Ben-Basat, S. (1980): Trickle irrigation and fertilization in the Northern Arava valley in Israel: Bell pepper. Agricultural Research Organization, Bet-Dagan, Israel (Hebrew).

Bar-Yosef, B., Kramer, S., Nutman, I. and Ben-Basat, S. (1981): Trickle irrigation and fertilization in the Northern Arava Valley in Israel: Egg-plants. Agricultural Reseach Organization, Bet Dagan, Israel (Hebrew).

Bar-Yosef, B. and Lambert, J.R. (1981): Corn and cotton root growth in response to soil impedance and water potential. Soil Sci. Soc. Am. J. 45: 930-935.

Bar-Yosef, B. and Sagiv, B. (1982a): Response of tomato to N and water applied via a trickle irrigation system. I. Nitrogen. Agron. J. 74: 633-737.

Bar-Yosef, B. and Sagiv, B. (1982b): Trickle irrigation and fertilization of Iceberg lettuce. Proc. 9th Intern. Plant Nutrition Colloquium. Warwick University, England, Vol. I: 33-38.

Bar-Yosef, B., Kramer, S. and Ben-Basat, S. (1982): Trickle irrigation and fertilization in the Northern Arava Valley in Israel: Fresh tomatoes (cv. 675). Agricultural Research Organization, Bet Dagan, Israel (Hebrew).

Bar-Yosef, B. and Sagiv, B. (1985): Potassium supply to field crops grown under drip irrigation and fertilization. Proc. K Symposium, International Potash Institute, Pretoria, pp. 185-188.

Bar-Yosef, B., Sagiv, B. and Markovitch, T. (1989): Sweet corn response to surface and subsurface trickle P fertigation. Agron. J. 74: 640-644.

Bar-Yosef, B. (1991): Vegetable production and fruit yield and quality under combined trickle irrigation and fertilization. FAO/ECE symp. on methods and concepts for the use of organic and chemical fertilizers. Geneva, Jan. 1991.

Bar-Yosef, B., Matan, E., Levkovich, I., Assaf, A. and Dayan, E. (1992): Response of greenhouse tomatoes (cv. F-144 and F-175) to irrigation and fertilization in the Besor area. Report on project 30-170-92, Agricultural Research Organization, Israel (Hebrew).

Bar-Yosef, B. and Imas, P. (1995a): Tomato response to phosphorus nutrition via drip fertigation. Proc. Fifth Intern. Microirrigation Cong., Orlando, FL. pp. 200-208. American Soc. Agric. Engineers.

Bar-Yosef, B. and Imas, P. (1995b): Orthophosphate solubility in waters of different ionic composition. Fertilizer Res. (in press).

Bar-Yosef., B., Keinan, M., Sternbaum, B., Levkovich, I., Markovich, T., Rosenberg, R. and Soriano, S. (1995): Muskmelon (cv. Arava) response to N concentration in water, NH_4:NO_3 ratio and greenhouse temperature. Report on project 301-0211-95, Agricultural Research Organization, Israel (Hebrew).

Beese, F., Horton, R. and Wierenga, P.J. (1982): Growth and yield response of chili pepper to trickle irrigation. Agron. J. 74: 556-561.

Ben Asher, J., Gordon, J.M., Liner, A. and Zarmi, Y. (1982): Nutrient uptake and supply to tomato plants in water culture system. Agron. J. 74: 640-644.

Bresler, E. (1975): Two-dimensional transport of solutes during nonsteady infiltration from a trickler source. Soil Sci. Soc. Am. Proc. 39: 604-613.

Bresler, E., McNeal, B.L. and Carter, D.L. (1982): Saline and sodic soils. Springer-Verlag, New York.

Bucks, D.A., Nakayama, F.S. and Warrick, A.W. (1982): Principles, practices and potentialities of trickle (drip) irrigation. Adv. Irrigation I: 220-298.

Cassell, D.K. and Klute, A. (1986): Water potential: tensiometry. *In*: A. Klute (ed): Methods of Soil Analysis. Part 1. pp. 563-596. Series in Agron. No. 9. Am. Soc. of Agron. Madison, WI, USA.

Dafne, O. (1984): Nitrogen effect on dry matter production, mineral absorption, yield and quality of processing tomatoes. MSc thesis submitted to the Faculty of Agriculture, The Hebrew University of Jerusalem, Israel (Hebrew).

Dasberg, S. and Bresler, E. (1985): Drip Irrigation Manual. International Irrigation Information Center, Publication No. 9, Bet Dagan, Israel.

Feigin, A. and Sagiv, B. (1971): Broccoli response to manure and N fertilization in a loessial soil in southern Israel. Report on project 401-10102, Agricultural Research Organization, Israel (Hebrew).

Feigin, A., Sagiv, B., Aviram, H. and Zipilevich, Y. (1976): Celery response to manure and N fertilization in a loessial soil in southern Israel. Report on project 301-046, Agricultural Research Organization, Israel (Hebrew).

Feigin, A., Zwibell, M., Rylski, I., Zamir, N. and Levav, N. (1979): The effect of ammonium/nitrate ratio in the nutrient solution on tomato yield and quality. Acta Hort. 98: 149-160.

Feigin, A. and Sagiv, B. (1982): Dry matter and nitrogen accumulation in irrigated autumn and spring potatoes grown in arid zone. Proc. 9th Intern. Plant Nutrition colloq. Warwick Univ., England. Vol. I pp. 168-173.
Feigin, A., Ginzburg, C., Gilead, S. and Ackerman, A. (1986): Effect of NH_4/NH_3 ratio in nutrient solution on growth and yield of greenhouse roses. Acta Hort. 189: 127-132.
Fishman, S. and Bar-Yosef, B. (1995): Simulation of N uptake and partitioning in potato plants in relation to yield: Model description and sensitivity analysis. Proc. Potato simulation Workshop, Wageningen, The Netherlands, 1994.
Fried, M. and Broeshart, H. (1967): The soil-plant system in relation to inorganic nutrition. Academic Press, New York.
Ganmore-Neumann, Ruth and Kafkafi, U. (1980): Root temperature and percentage NO_3/NH_4 effect on tomato plant development. I. Morphology and growth. Agron. J. 72: 758-761.
Ganmor-Neumann, Ruth and Kafkafi, U. (1983): The effect of root temperature and NO_3/NH_4 ratio on strawberry plants. I. Growth, flowering and root development. Agron. J. 75: 941-947.
Gardner, W.H. (1986): Water content. *In*: A. Klute (ed): Methods of Soil Analysis. Part I. pp. 493-544. Series in Agron. no. 9. Am. Soc. Agron. Madison WI, USA.
Glass, A.D.M. and Perley, J.E. (1980): Varietal differences in potassium uptake by barley. Potash Rev. 12: 1-9.
Goldberg, D., Gornat, B. and Rimon, D. (1976): Drip Irrigation Principles, Design and Agricultural Practices. Drip Irrigation Scientific Publications, Kfar Shmariahu, Israel.
Halevy, J. (1976): Growth rate and nutrient uptake of two cotton cultivars grown under irrigation. Agron. J. 68: 701-705.
Hatfield, J.L. and Fuchs, M. (1990): Evapotranspiration models. *In*: G.J. Hoffman, T.A. Howell and K.H. Solomon (ed): Management of Farm Irrigation Systems. pp. 33-59. ASAE Monograph, The American Society of Agricultural Engineers, St. Joseph, MI.
Hoffman, G.J., Rhoades, J.D., Letey, J. and Fang Sheng (1990): Salinity management. *In*: G.J. Hoffman, T.A. Howell and K.H. Solomon (eds): Management of Farm Irrigation Systems. pp. 667-715. ASAE Monograph, The American Society of Agricultural Engineers, St. Joseph, MI.
Jones, C.A. and Kiniry, J.R. (1986): CERES-MAIZE. A simulation model of maize growth and development. Texas A&M University Press. Tx.
Marani, A. and Baker, D.N. (1981): Development of a predictive dynamic simulation model of growth and yield in Acala cotton. BSF report 1708/78, The Hebrew University of Jerusalem, Faculty of Agriculture, Israel.

Martin, D.L., Stegman, E.C. and Fereres, E. (1990): *In*: G.J. Hoffman, T.A. Howell and K.H. Solomon (eds): Management of Farm Irrigation Systems. pp. 155-203. ASAE Monograph, The American Society of Agricultural Engineers, St. Joseph, MI.

Mengel, K. and Kirkby, E.A. (1987): Principles of plant nutrition. 4th ed. International Potash Institute, Bern, Switzerland.

Olsen, S.R. and Kemper, W.D. (1968): Movement of nutrients to plant roots. Adv. Agron. 20: 91-151.

Rhoades, J.D. and Oster, J.D. (1986): Solute content. *In*: A. Klute (ed): Methods of Soil Analysis, Part 1. pp. 563-596. Series in Agron. No 9. Am. Soc. Agron. Madison WI, USA.

Sagiv, B., Bar-Yosef, B. and Kafkafi, U. (1977): Drip irrigation and fertilization in Besor: Bell pepper. Agricultural Research Organization, Bet Dagan, Israel (Hebrew).

Sagiv, B., Bar-Yosef, B. and Eliah, E. (1980): Drip irrigation and fertilization of sping muskmelon at Besor. Special Publication no. 17. Division of Scientific Publications, The Volcani Center, Bet-Dagan, Israel (Hebrew).

Sagiv, B., Bar-Yosef, B., Eliah, E. and Mini, A. (1983): Response of sweet corn to trickle irrigation and N fertilization under drip and sprinkle irrigation. Report 301/064. Agricultural Research Organization, Bet Dagan, Israel.

Sagiv, B., Feigin, A., Hadas, A., Keinan, M. and Markovich, T. (1992): Response of drip irrigated chinese cabbage to manure and municipal refuse composts and inorganic N fertilization. Report on project 301-154-90, Agricultural research organization, Israel.

Sagiv, B., Bar-Yosef, B., Hadas, A., Soriano, S. and Levkovich, I. (1995): Response of drip irrigated carrot (cv. Buror) to manure and municipal refuse composts and inorganic N fertilization. Report on project 301-154-90, Agricultural research organization, Israel.

Shevah, Y. and Waldman, M. (1989): Advances in management of fertilizer application and the resulting effect on the pollution load in soil. *In*: B. Bar-Yosef, N.J. Barrow and J. Goldshmid (eds.) Inorganic Contaminants in the Vadose Zone. Springer-Verlag, New York. pp. 179-189.

Stanford, G. and Epstein, E. (1974): Nitrogen mineralization water relations in soils. Soil Sci. Soc. Am. Proc. 38: 103-107.

Stanhill, G. (1985): Water use efficiency. Adv. Agron. 39: 53-85.

Tillitson, W.R., Robbins, C.W., Wagenet, R.J. and Hanks, R.J. (1980): Soil water, solute and plant growth simulation. Utah Agricultural Experiment Station Bulletin 502.

Topp, G.C. and Davis, J.L. (1985): Time-domain reflectometry (TDR) and its application to irrigation scheduling. p. 107-127. *In*: D. Hillel (ed.) Advances in irrigation. Vol 3. Academic Press, Orlando, FL.

US Salinity Laboratory Staff (1954): Diagnosis and improvement of saline and alkali soils. USDA Agric. Handbook No. 60.

Yarwood, C.E. (1978): Water and the infection process. *In*: Water deficit and plant growth. T.T. Kozlowski (ed.) 5: 141-165. Academic Press, N.Y.