Tools and strategies for sustainable nitrogen fertilisation of vegetable crops

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Abstract

In intensive vegetable production, N fertiliser applications often contribute to a supply of N that appreciably exceeds crop N requirements resulting in the loss of N to the environment which can result in NO_3^- contamination of water bodies. There is range of tools and strategies that can assist vegetable growers to improve N management. These include various methods based on soil analysis or estimation of the soil N supply, N balance calculations, methods based on plant analysis, methods based on monitoring crops with optical sensors, and the use of computerised decision support systems based on simulation models or data bases. Use of these tools has been demonstrated to appreciably reduce fertiliser N application and N losses while maintaining production. The selection of tools to be used by a grower will be influenced by factors such as availability, the grower's technical level, and economic considerations. For fertigation systems with high frequency N application, a combination of planning method such as a decision support system and a monitoring method is recommended. Additional tools that can assist in demonstrating to stakeholders the benefit of improved N management are simulation models that provide scenario analysis. Fundamental strategies for improving N fertiliser management are to consider all N sources such as root zone soil mineral N and N mineralised from organic materials, and to partition N application so that it coincides with crop N demand.

Keywords: fertiliser, nitrogen losses, nitrate leaching, soil testing, crop testing, sap analysis, optical sensors, simulation models, decision support systems, nitrification inhibitors, slow release fertilisers, controlled release fertilisers

1. Introduction

Intensive vegetable production systems are commonly associated with appreciable loss of nitrogen (N) to the environment. Significant nitrate (NO_3^-) leaching loss often occurs (e.g. Min et al., 2011; Ramos et al., 2002; Thompson et al., 2007a; Vázquez et al., 2006; Zotarelli al., 2007) as a consequence of the common practices of excessive N fertiliser and irrigation application (Fereres et al., 2003; Meisinger et al., 2008; Pratt, 1984; Thompson et al., 2007b). In addition, vegetable crops often have shallow rooting systems and short periods of high N demand, both of which favour NO_3^- leaching.

Substantial NO_3^- contamination of underlying aquifers can result from NO_3^- leaching loss from vegetable production systems (e.g. Harter and Lund, 2012; Ju et al., 2006; Kraft and Stites, 2003; Pulido-Bosch et al., 2000). Excessive N fertiliser application of vegetable crops is also associated with enhanced emissions of the greenhouse gas nitrous oxide (N_2O) (e.g. Min et al., 2012; Xiong et al., 2006). Also, N enriched drainage water can contribute to eutrophication of surface waters. In addition to the environmental consequences of N losses from vegetable production, excessive N application represents a repeated, appreciable and unnecessary expense to vegetable growers.

Concerns over human health consequences (Follett and Follett, 2001) have prompted social and political pressure to reduce NO_3^- contamination of aquifers and eutrophication of surface water with NO_3^- originating from agriculture and horticulture. For example, in the European Union (EU), two pieces of legislation, the Nitrates Directive (Anon. 1991) and the Water Framework Directive (Anon. 2000) are forcing the imposition of improved management of N fertiliser. These directives require all farmers, in areas where there are environmental problems caused by N fertiliser use, to adopt improved N management practices. Regions within the EU where there is aquifer NO_3^- contamination or surface water eutrophication, or a high risk of either occurring, are designated as being Nitrate Vulnerable Zones (NVZ) as stipulated by the Nitrates Directive. These regions must then demonstrate improved water quality. Currently, these pieces of legislation have been most strongly implemented in The Netherlands, Belgium (Flanders), Denmark and Germany; it is considered to be a matter of time before there is strong implementation throughout the rest of the EU.

Vegetable growers generally apply N on the basis of experience, either their own or that of technical advisors (Chen et al., 2004; Thompson et al., 2007b; Tremblay and Bélec, 2006). The adoption of science-based procedures to determine N fertiliser rates will contribute to reducing the large N losses to the environment that often occur in intensive vegetable production. Procedures to assist with the N management of vegetable crops must be adapted to the characteristics of the cropping systems. Some relevant characteristics are the variation in planting dates and cropping seasons, multiple cropping within a year, the diversity of species and the considerable differences in morphology between species, climatic requirements, the lengths of growing season between species, and the variety of cultivars of a species. Some characteristics of vegetable production favour the adoption of improved management procedures such as the intensity of crop management, the high value of the crops, and the generally small field sizes. A consideration is the tendency for increased adoption of fertigation in combination with drip or sprinkler irrigation; with these combined systems, high frequency N application often occurs. High frequency N application opens up possibilities for adaptive management (Granados et al., 2013) compared to the traditional approach of a pre-planting application and one to three side-dress application. Frequent N application has implications for the type of recommendation systems that can be used.

A wide variety of approaches have been developed to assist with the N management of vegetable crops. These include methods based on soil analysis, plant analysis, computer-based decision support systems, the use of proximal optical sensors to rapidly assess crop nutrient status, the use of nitrification inhibitors, and the use slow and controlled release fertilisers. This chapter will review the various methods that are in use on commercial farms and that have been the subject of recent research programs.

2. Nature of output from tools for N management of vegetable crops

Methods to assist in N fertiliser management provide either: (a) a recommendation of the quantity of mineral fertiliser N to apply, or (b) an assessment of the N status of the crop or of the N supply from the soil. Methods based on soil testing and N balance calculations generally provide estimates of the quantity of fertiliser N to apply. Methods that assess crop N status such as plant analysis and the use of proximal optical sensors require interpretation procedures to inform users of whether, at the time of assessment, a crop has deficient, sufficient or excessive N status. To make such an assessment, generally either sufficiency values or sufficiency ranges are commonly used.

A sufficiency value distinguishes between deficiency (below the value) and sufficiency (above the value). Sufficiency values are also referred to as reference or threshold values. A sufficiency range consists of lower and upper limit values; the lower limit value distinguishing between deficiency and sufficiency, and the upper limit value between sufficiency and excess. Sufficiency values and ranges are often determined for phenological (development) phases for a given species. They can also be expressed on the basis of thermal time. The use of phenological phases or thermal time provides flexibility to deal with the differences in planting dates and growing seasons that occur with vegetable cropping.

To determine sufficiency values and ranges, different approaches have been used such as experience, yield analysis or the use of indicators of crop N status. Two indicators that have been used, particularly with proximal optical sensors, are the Nitrogen Nutrition Index (NNI) (Lemaire et al., 2008) and the Sufficiency Index (SI) (Samborski et al., 2009). These are explained in Sections 5.2 and 6.1, respectively, of this chapter. With methods that assess crop N status, and in some cases the immediate soil N supply, the subsequent decision on the rate of N fertiliser application is generally an adjustment to a previously-determined rate or standard plan of N fertilisation. These approaches are well-suited to where frequent small N applications are made because applications made after testing can be adjusted thereby ensuring optimal management throughout the crop.

3. Methods based on soil analysis or soil N supply

With soil testing approaches, the N fertiliser rate is adjusted in response to the amount of soil mineral N in the root zone. These can be considered as site specific approaches, in which the N supplied by the soil is taken into account using either relationships derived from (a) fertiliser trials or experience, or (b) mathematical calculations.

3.1. Nmin system

An approach used with field-grown vegetable crops in North-western and Central Europe is the Nmin system that was described originally by Wehrmann and Scharpf (1979) for use with cereals, and later by Wehrmann and Scharpf (1986) and Scharpf (1991) for use with vegetables. “Nmin” refers to mineral N, and not to N mineralised from organic material. In this approach, the recommended amount of mineral N fertiliser is influenced by the amount of soil mineral N in the root zone at planting. Field trials are used to obtain “N target values” which represents the required total supply of mineral N to ensure that the crop does not experience a N limitation. The total mineral N supply is the sum of applied mineral fertiliser N and soil mineral N in the root zone. To estimate the recommended mineral N fertiliser application rate, for a given crop, soil mineral N in the root zone, determined at the beginning of the crop is subtracted from the N target value. Hereafter, this procedure is referred to as the basic Nmin system.

Individual N target values are required for all crops, and are determined from a number of fertiliser trials conducted for a given species in a given region (Feller and Fink, 2002). The root zone depth varies between crops, ranging from 15 cm for lamb's lettuce to 90 cm for some cabbage cultivars and Brussels sprouts (Feller et al., 2015).

The basic Nmin system is described by:

N fertiliser recommendation = N target value – soil mineral N in root zone Eq. 1

Soil mineral N in the root zone (Nmin) refers to the sum of NO_3^-–N plus NH_4^+–N. In practice, however, generally just NO_3^-–N is measured because normally almost all soil mineral N is in the form of NO_3^-–N because of rapid nitrification of NH_4^+–N. The additional measurement of NH_4^+–N is recommended when appreciable amounts are expected such as after recent application of organic fertilisers or mineral NH_4^+ fertilisers. The Nmin system does not explicitly consider N mineralisation, because it is implicitly considered in the experimental determination of the N target value. Without calling it the Nmin system, Neeteson (1994) suggested a very similar approach. Using numerous field trials, inverse linear relationships were derived between the optimal fertiliser N rate and root zone soil mineral N for each species within a region (Neeteson, 1994).

The Nmin system uses experimentally-determined N target values, which are derived from fertiliser trials conducted at representative field sites. Given the large number of combinations of vegetable species, cultivars, locations, and distinct soil types, very large numbers of field trials would be required to develop a comprehensive set of N target values for all the commercially-grown vegetable species within a region (Feller and Fink, 2002). The requirement for experimentally-determined target values is a major practical limitation of the Nmin system. Where active and well-funded Extension services exist, it is likely that N target values could only be determined for a number of major species. However, many regions lack Extension services with the funding and means to conduct numerous fertiliser trials. Another general limitation of the Nmin system is that the recommendations are made for average crops in a region

The N target value cannot readily be adapted to field specific conditions, such as variations in expected yield or expected N mineralisation from soil organic matter. The Nmin system provides a single N fertiliser recommendation for a crop; it does not provide information on the partitioning of the fertiliser application.

3.2. The KNS system

The KNS (Kulturbegleitende-Nmin-Sollwerte) system developed by Lorenz et al. (1989) is a development of the basic Nmin system that also uses the concept of the N target value. The N target value, used by the KNS system, is calculated for an individual crop using a very simple modelling approach. The KNS system does not require comprehensive fertiliser trials to experimentally determine N target values and does not assume fixed yields. This N recommendation system is used in parts of north-western and Central Europe, and is the most commonly used system in Flanders, Belgium. The KNS system considers root zone mineral N at planting and also during the crop growth. The method allows calculation of N target values at any time during crop growth. This potentially enables the grower to adapt the fertilisation plan after unforeseen events, such as very high rainfall that leach N from the root zone, high N mineralisation or unexpected crop growth or development because of weather fluctuations. For most crops, N recommendations are made for two periods during crop growth; for crops with long growing cycles, three periods are recommended. The essential idea of the KNS system is to improve the accuracy of N fertiliser recommendations by applying part of the total N requirement at the beginning and to adjust the subsequent N top dressing according to a very recent soil mineral N analysis. It should be noted that this approach works only if two (or three) soil mineral N analyses are made for each crop. In practice, growers can be reluctant to make even one analysis per crop unless obliged to do so.

The KNS system considers a buffer value for root zone soil mineral N (N buffer) below which production is N limited (Ziegler et al., 1996); the buffer value is sometimes referred to as the required “residual” amount of soil mineral N in the root zone. The buffer value (in kg N ha^{-1}) is added to the anticipated crop N uptake (N crop) for a given period (e.g. several weeks) to calculate the N target value for that period (Eq. 2).

$$\text{N target value} = \text{N crop} + \text{N buffer} \qquad \text{Eq. 2}$$

where N crop is crop N uptake during the specified period, N buffer is the buffer value of required soil mineral N at the end of the specified period.

The N target value in the KNS system is the amount of mineral N that should be made available to the crop to ensure there is no N limitation during the specified period. The procedure used in the KNS system is described subsequently. An example is provided in Text Box 1 and table 1; this is an adapted example of that described by Ziegler et al. (1996).

The N crop value, used to calculate the N target value, is the sum of weekly or daily crop N uptake values for the specified period. The N crop values are provided to users in tables or graphs and are derived from results of local fertiliser trials, surveys on growers' fields and published studies. The number of field trials to establish the KNS system is appreciably less than required for the basic Nmin system. To accommodate higher or lower yields than the average yields considered by the KNS system, manual adjustment to consider site specific features can be used to increase or lower crop N values.

The required soil mineral N buffer values are derived empirically. In general, N buffer values at final harvest are relatively high if there is a high risk of insufficient N causing a reduction in yield or in product quality. For example, for broccoli and cauliflower a soil mineral N buffer of 80 kg N ha^{-1} is used to ensure marketable head sizes. Very low N buffer values (e.g. 0 kg N ha^{-1}) are applied if excessive N supply at harvest may cause marketing problems, such as high nitrate content in carrots grown for baby food. For most crops, the N buffer value is set to 40 kg N ha^{-1}. Crop specific properties may be considered such as with leek where low root density and low potential nitrate uptake per root length are considered to justify a higher buffer value of 60 kg N ha^{-1}.

Whereas N mineralisation is implicitly considered in the experimentally-derived N target values used by the basic Nmin system, N mineralisation should be explicitly considered in the KNS system. Lorenz et al. (1989) suggested for the Rhineland Palatinate region in Germany a fixed value of 5.5 kg N ha^{-1} week^{-1} for N mineralisation from soil organic matter. The full calculation for the N fertiliser recommendation in the KNS system is made according to equation 3.

N fertiliser recommendation = N crop + N buffer – (N mineralised from soil organic matter + soil mineral N in the root zone) Eq. 3

where N fertiliser recommendation, N crop and N mineralised from soil organic matter are for the specified period; N buffer is for the end of the specified period; and soil mineral N is determined at the start of the specified period. The specified period may be from planting or from a later period during the crop.

Text Box 1 Example of KNS system

Adapted from Ziegler et al. (1996).

Determination of N fertiliser recommendation using the KNS system for a spring lettuce crop, with following characteristics:

- Total crop N uptake of 100 kg N ha^{-1}
- Rooting depth of 30 cm
- N fertiliser applied at planting and at 6 weeks
- Soil mineral N determined at planting and at 6 weeks to be 25 and 40 kg N ha^{-1}, respectively
- Assumed N mineralisation of 5 kg N ha^{-1} week^{-1}

Table 1: Information used to calculate N fertiliser recommendation

Weeks after planting	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Crop N uptake (kg N ha^{-1} week^{-1})	0	1	3	6	10	15	20	30	15
Soil mineral N buffer (kg N ha^{-1})	60					40			40
N target value at planting and for side dressing in week 6 (kg N ha^{-1})	80					120			
N mineralisation from soil organic matter (kg N ha^{-1} week^{-1})	5	5	5	5	5	5	5	5	5
Soil mineral N determined in 0-30 cm soil (kg N ha^{-1})	25					40			
Recommended N fertiliser rate at planting and side dressing in week 6 (kg N ha^{-1})	30					60			

<u>Calculation of N target values</u>:

1) N target value at planting

= (Anticipated N uptake for weeks 1–5) + soil min N buffer

= (0 + 1 + 3 + 6 + 10) + 60 = 80 kg N ha^{-1}

2) N target value week 6

= (Anticipated N uptake for weeks 6–9) + soil min N buffer

= (15 + 20 + 30 + 15) + 40 = 120 kg N ha^{-1}

Calculation of recommended N fertiliser rates: = N target value - soil mineral N - N mineralisation

1) N fertiliser at planting = 80 - 25 - (5*5) = 30 kg N ha^{-1}

2) N fertiliser at week 6 = 120 - 40 - (4*5) = 60 kg N ha^{-1}

3.3. The N-Expert system

The N-Expert system, originally published by Fink and Scharpf (1993) is a further development of the KNS system. Fink and Scharpf (1993) observed a systematic difference between N target values, calculated according to the KNS system (Eq. 2), and experimentally-derived N target values. To overcome these systematic differences they included a general N loss term for the calculation of N target values. There are several specific N loss pathways, some such as NO_3^- leaching or gaseous N losses are “real N losses” in that N is physically lost from the field whereas other pathways are "apparent N losses" in that they temporarily make N unavailable for the crop, e.g. N immobilisation. Based on the study of Fink and Scharpf (2000), a N recovery of 80 % of total N supply is used in the N-Expert system. The estimated unrecovered N (that is assumed to be lost) and the estimated mineralisation from soil organic matter are combined in a component called “apparent N net mineralisation” (Eq. 4) (Feller and Fink, 2002).

N target value = N crop + N buffer – apparent net N mineralisation Eq. 4

Using this calculated approach (Eq. 4), Feller and Fink (2002) obtained good agreement between calculated N target values and experimentally-determined N target value for 24 different vegetable crops, as presented in Figure 1.

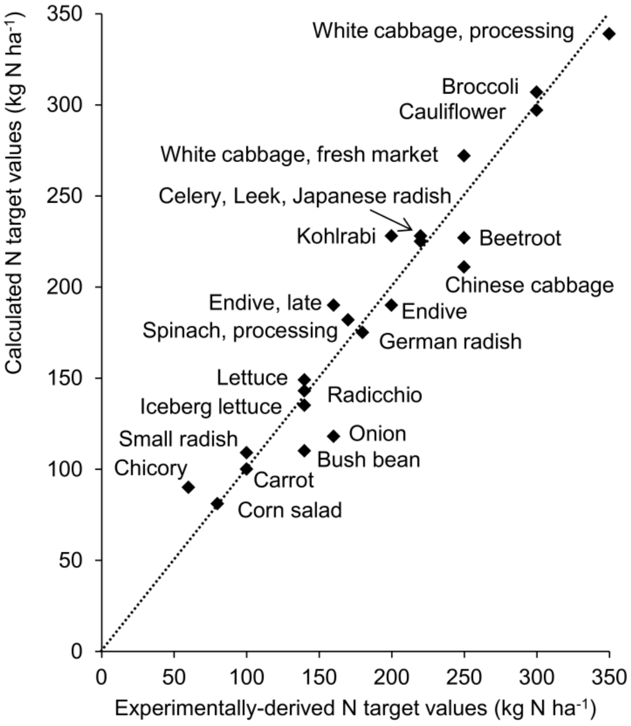

Figure 1. N target values experimentally-derived by Scharpf (1991) related to N target values calculated with N-Expert. Dashed line is y=x. Reproduced with permission from Feller, C., Fink, M. 2002. Nmin target values for field vegetables. Acta Horticulturae 571, 195-201 published by the International Society of Horticultural Science.

The calculation of N fertiliser recommendation with the N-Expert system is the same as with the KNS system, the only difference being that the component “N mineralised from soil organic matter” in equation 3 is substituted by “apparent net N mineralisation”" which considers the net effect of N mineralisation and of both real and apparent N losses, during crop growth.

In view of the expense of soil mineral N analyses and the reluctance of growers to undertake soil analyses, the authors of the N-Expert system suggest only one analysis per crop (Feller et al., 2015). For crops that are grown from transplants, soil sampling and subsequent fertiliser application are recommended shortly before planting. For sown crops with a long germination period and slow early development, soil sampling and fertiliser application are recommended four or six weeks after sowing. A comprehensive, up-to-date table comprising N-Expert's N target values for all commercially relevant field vegetables in northern Europe is available as a free download by Feller et al. (2015).

The recently revised (September 2015) N-Expert 4 decision support software (in German and English) together with support (in German and English) and explanatory information (in German) is available at http://www.igzev.de/n-expert/?lang=en. The N-Expert decision support system is further discussed in Section 8.2 on Decision Support Systems. A modified, previous version of the N-Expert system was used in China with amaranth, spinach and cauliflower; compared to conventional management, yields were similar, less N was applied and there was less residual soil mineral N (Chen et al., 2005).

3.4.The Pre Side-dress Nitrate Test (PSNT)

The Pre Side-dress Nitrate Test (PSNT) measures root zone soil NO_3^-–N during the crop cycle immediately prior to the main side-dressing N application that precedes the period of rapid vegetative growth (Hartz, 2006; Heckman, 2002; Meisinger et al., 2008). Only NO_3^-–N is determined because generally almost all soil mineral N is in the form of NO_3^-–N. The PSNT is primarily used to assess whether side-dress N application is required (Hartz, 2006; Meisinger et al., 2008). It was developed for maize in North America and has been proposed as a N management system for grain maize in numerous US states and provinces of Canada. For maize, soil is sampled to 30 cm when the crop is 15–30 cm tall, and when the soil NO_3^-–N content is >25 mg kg^{-1}, the soil N supply is considered to be sufficient and fertiliser N is not required (Meisinger et al., 2008).

The use of the PSNT with different vegetable crops such as tomato, lettuce, cabbage, celery, pepper and pumpkin has been evaluated (e.g. Breschini and Hartz, 2002; Bottoms et al., 2012; Hartz et al., 2000; Heckman, 2002; Hartz, 2006). Breschini and Hartz (2002) demonstrated that use of the PSNT appreciably reduced N fertiliser applications in commercial lettuce crops. As general Extension guidelines for a wide range of vegetable crops including cabbage, cauliflower, broccoli, lettuce, cucumber, muskmelon, pepper, tomato and eggplant, Heckman (2002) recommended sampling to 30 cm and the use of limits of 25–30 mg NO_3^-–N kg^{-1} above which fertiliser N was not required. Hartz (2006) recommended general limits for vegetable crops of 20–25 mg NO_3^-–N kg^{-1}. The lower reference value of 20 mg NO_3^-–N kg^{-1} was specifically recommended for lettuce and celery by Hartz et al. (2000). The PSNT has been shown to be effective for identifying whether or not to apply side-dress N for field-grown vegetable crops.

The PSNT is primarily used to assess whether side-dress N application is required, and there is general agreement on the reference values for making this assessment. In commercial practice with grain maize, there are generally few cases where some side-dress N is not required, and these can often be suspected without the use of the PSNT, which limits the usefulness of the PSNT in practice. A major general limitation of the PSNT is the very limited availability of relationships between the results of the test and N fertiliser recommendations that are species and region specific There have been some derivations of these relationships for determining N fertiliser recommendations from PSNT results. Schmidt et al. (2009) reported relationships for calculating N fertiliser recommendations for maize in Pennsylvania for PSNT values of <26 mg NO_3^-–N kg^{-1}. Breschini and Hartz (2002) reported a simple general procedure to calculate recommended N fertiliser applications for vegetable crops using the PSNT; the amount of N added being that which increased the soil NO_3^-–N content in the root zone to the reference value, which was 20 mg kg^{-1} in their study. These authors presented a table that provided recommended rates of fertiliser N for soil NO_3^-–N contents of <20 mg kg^{-1}.

The use of the PSNT is restricted to field-grown crops receiving pre-plant and side dress N applications. As its name indicates, the PSNT is intended to assist with single side-dress N applications. For use with vegetable crops receiving frequent N application through fertigation, frequent soil sampling, extraction and analysis would be required.

3.5. Root zone N management

The root zone N management system reported in several Chinese studies, with greenhouse-grown tomato (He et al., 2007; Ren et al., 2010) and cucumber (Guo et al., 2008), is based on the KNS system and aims to maintain a buffer amount of root zone soil mineral N throughout the crop. The KNS system and the concept of the buffer amount of root zone soil mineral were defined in Section 3.2 of this chapter. With root zone N management, fertiliser N recommendations for several side-dress applications are based on the difference between N target value and root zone (generally 0-30 cm) soil mineral N and the NO_3^-–N applied in irrigation water according to equation 5.

Recommended fertiliser N = N target value – root zone soil mineral N – NO_3^-–N from irrigation water. Eq. 5

In China, irrigation water commonly has a sufficient [NO_3^-] to contribute appreciable amounts of readily available N to crops. Therefore, the amount of NO_3^-–N added in irrigation water was included in equation 5 to calculate the N fertiliser requirement.

In the studies of He et al. (2007), Guo et al. (2008) and Ren et al. (2010), for each of the several N side-dress applications, the amount of root zone mineral N was determined in order to calculate the corresponding N fertiliser recommendation. The N target value, as used in the KNS system, is crop N uptake plus the buffer value (see Section 3.2 of this chapter). For tomato, both He et al. (2007) and Ren et al. (2010) used fixed N target values of 200–300 kg N ha^{-1} which were most commonly 200 kg N ha^{-1} for each side dress application. For both of these studies, the derivation of the N target values was not clearly explained. For cucumber, Guo et al. (2008) calculated N target values as the sum of (a) buffer values of 200 kg N ha^{-1} for 0–30 cm soil, and (b) crop N uptake which was estimated using simple equations based on time since transplanting. These authors used different crop N uptake equations for autumn-winter and winter-spring growing seasons. Compared to conventional N management practices in Chinese greenhouse vegetable production, in which very excessive amounts of N are applied (Chen et al., 2004), the use of the root zone N management system consistently resulted in considerable reductions in N fertiliser application while maintaining fruit production (He et al., 2007; Guo et al., 2008; Ren et al., 2010). Nevertheless, appreciable apparent N losses still occurred with the use of root zone N management in these studies suggesting that further improvements in N use efficiency could be obtained by additional approaches such as improved irrigation management and improved estimation of N mineralisation from manures (He et al., 2007; Ren et al., 2010).

As experimental studies in the context of the massive N surpluses associated with Chinese greenhouse vegetable production (Chen et al., 2004; Ju et al., 2006), these studies (Guo et al., 2008; He et al., 2007; Ren et al., 2010) demonstrate that science–based management can substantially reduce N addition and apparent N loss while maintaining production. In the studies of He et al. (2007), Guo et al. (2008) and Ren et al. (2010), soil was extracted with a dilute calcium chloride solution and the extract was analysed in the laboratory for NH_4^+–N and NO_3^-–N. He et al. (2007) and Ren et al. (2010) also analysed the extracts for NO_3^-–N with test strips as a rapid analysis procedure. The willingness of growers to conduct and pay for soil analyses is discussed in Section 3.10 of this chapter.

3.6. Soil N Supply Indices

Soil N supply (SNS) indices provide an approach in which the soil N supply is estimated rather than measured. In England and Wales, an index system is used to estimate the “Soil N Supply” (SNS) where soil sampling and analysis have not been conducted. The “Fertiliser Manual RB209” (AHDB, 2015) enables SNS Index values to be estimated by using a series of look-up tables for a given field and to provide the recommended N fertiliser rate for a given crop in that field. The SNS Indices estimate soil mineral N available to the crop which includes estimated N mineralised from organic material during the crop. SNS indices are determined for a specific field by considering average annual rainfall, soil texture and residues from the preceding crop. The SNS indices have values of 0 to 6, and each index value corresponds to a different incremental supply of soil mineral N in the root zone (in kg N ha^{-1}). Measurements of soil mineral N, at planting, can be incorporated into the recommendation procedure and are suggested for certain situations such as when there are high or uncertain amounts of crop residue (Rahn, 2012).

The use of SNS indices to determine N fertiliser recommendations takes place in two stages. Firstly, the SNS Index is determined for the site, and then for a given crop grown on that site, the corresponding N fertiliser rate is determined. For example, in a low rainfall zone (500–600 mm) with a medium-textured soil, the SNS Indices of 1, 3 and 4 correspond to estimated low, medium and high amounts of N in the residues of the previous vegetable crop. The estimated amounts of crop residue N are a function of the previous species; there are three classes: low (e.g. carrot, onion), medium (e.g. lettuce, leek) and high (e.g. Brussels sprouts). The SNS indices of 1, 3 and 4, in this example, correspond to estimated soil N supply values of 61–80, 101–120, and 121–160 kg N ha^{-1}, respectively. For a lettuce crop, for SNS indices of 1, 3 and 4, the corresponding recommended N fertiliser rate are 180, 150 and 125 kg N ha^{-1}. Rahn (2012) described the use of the RB209 Fertiliser Manual to determine N fertiliser recommendations.

As described in section 8.3 of this chapter, the software program PLANET (DEFRA, 2014) provides recommendations based on estimated SNS Index values and also enables record-keeping. Both the RB209 Fertiliser Manual and the PLANET software are freely available on Internet. Many growers in England and Wales have a copy of RB209 or PLANET. While it is difficult to know how many growers actually regularly use these recommendations; it seems many growers do so (C. Rahn, University of Warwick, United Kingdom, personal communication). A revision of the RB209 Fertiliser Manual, the AHDB (Agriculture and Horticulture Development Board) Nutrient Management Guide is scheduled for release in 2017.

3.7. Dutch 1:2 volume soil:water extract method

This method was developed for soil-grown crops in high technology greenhouses in The Netherlands where fertigation with frequent nutrient application is the standard practice. Species specific fertigation programs have been developed in which a standard nutrient solution is adjusted in response to the results of the analysis of extract obtained from a 1:2 volume, soil:water extraction that is conducted periodically throughout the crop (Sonneveld and Voogt, 2009). The species specific standard nutrient solution is also adjusted for cropping conditions such as water quality, crop development stage, and soil type. In this system, all mineral N is supplied by fertigation.

Because of frequent nutrient addition by fertigation, interest is in the immediately available nutrients in the soil, rather than the nutrient supply over longer time periods. To optimise the management of frequent nutrient addition, relatively frequent testing is necessary which requires simple and quick procedures to obtain and prepare samples. Composite soil samples are taken regularly, and extracted and analysed using the 1:2 volume (soil:water) extract method (Sonneveld and van den Ende, 1971; Sonneveld and Voogt, 2009; Sonneveld et al., 1990) which provides a good estimate of the [NO_3^-] in the soil solution and of total amount of immediately available soil mineral N per unit area. Additionally, information on the soil electrical conductivity (EC) and on the availability of other nutrients is provided (Sonneveld and Voogt, 2009; Sonneveld et al., 1990). The analytical results of the extract solution are compared with target values and limits for individual nutrients. These results are used to adjust the nutrient concentrations and the EC of the applied nutrient solution.

This method has been used by commercial growers in greenhouses in The Netherlands for a number of years (W. Voogt, University of Wageningen, personal communication), and recently has been adapted to greenhouse conditions in Italy (L.

Incrocci, University of Pisa, personal communication) and Greece (de Kreij et al., 2007). The sufficiency range values determined for crops in Italy are somewhat lower than those used in The Netherlands (L. Incrocci, University of Pisa, Italy, personal communication).

Unlike the previously described soil testing approaches, the 1:2 volume (soil:water) extract method was developed specifically for fertigated crops receiving high frequency nutrient application. The use of a composite soil sample, overcomes the issue of spatial variability that has been reported with localised measurements such as ceramic cup suction soil solution samplers (Section 3.8 of this chapter). While most use of the 1:2 volume (soil:water) extract method in The Netherlands, Italy and Greece has been with soil-grown greenhouse crops, it can be used with fertigated vegetable crops grown in open fields (W. Voogt, Wageningen University and Research, The Netherlands, personal communication).

3.8 Nitrate concentration of the soil solution in the root zone

The NO_3^- concentration ($[NO_3^-]$) of the soil solution in the root zone, sampled regularly during a crop with ceramic cup suction samplers, has been used as a method to assist in the N management of vegetable crops. Conceptually, this method provides control over the immediately available N (both in form and location) in the root zone. This method is best suited for use with vegetable crops receiving frequent N addition through combined fertigation and drip irrigation, with the sampler providing samples of soil solution from within the drip irrigation bulb where most roots are located.

In Israel, soil solution samplers are commonly used in commercial vegetable production using a sufficiency value of 5 mmol NO_3^- L^{-1} (S. Kramer, Israeli Ministry of Foreign Affairs, personal communication). Burt et al., (1995) and Hartz and Hochmuth

(1996) suggested the use of the root zone soil solution [NO_3^-] to assist in the N management of vegetable crops also using a sufficiency value of 5 mmol NO_3^- L^{-1}. Burt et al. (1995) commented that with frequent N application by combined fertigation/drip irrigation systems, the sufficiency values may be lower. Hartz (2003) commented that the high spatial variability of soil solution [NO_3^-] may limit the practical value of this approach. In greenhouse-grown vegetable crops with very frequent nutrient application through combined fertigation/drip irrigation, excessive N application was associated with increasing soil solution [NO_3^-] (Figure 2; Gallardo et al., 2006; Granados et al., 2013; Peña-Fleitas et al., 2015). These results suggest that an on-going tendency of increasing soil solution [NO_3^-] is an indicator of excessive N application with fertigated/drip irrigated vegetable crops, particularly where little drainage and therefore NO_3^- leaching occurs. The use of tendencies overcomes two issues: (1) the uncertainties associated with spatial variation of individual point measurements, and (2) the identification of sufficiency values and ranges (as discussed subsequently). Spatial variation may be a more important issue with commercial growers than in research studies because of grower reluctance to have a sufficient number (e.g. three or more) of replicated samplers within a field.

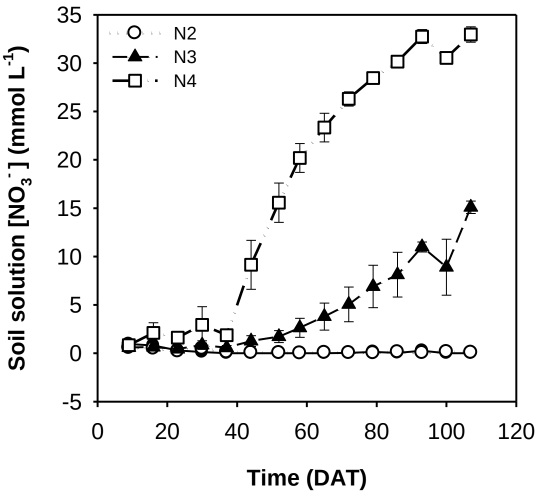

Figure 2. [NO_3^-] of root zone soil solution during a fertigated tomato crop grown in a greenhouse in SE Spain. The average N concentrations applied by fertigation/drip irrigation were 5, 13 and 22 mmol L^{-1} for treatments N2, N3 and N4, respectively. Values are means ± SE (n=4). DAT is days after transplanting. Reproduced with permission from Peña-Fleitas, T., Gallardo, M., Thompson, R.B., Farneselli, M., Padilla, F.M. (2015) Assessing crop N status of fertigated vegetable crops using plant and soil monitoring techniques, Annals of Applied Biology 167, 387-405, published by John Wiley and Sons.

In a pepper crop grown in a greenhouse in south-eastern (SE) Spain, Granados et al. (2013) maintained soil solution [NO_3^-] within a range of 8–12 mmol L^{-1} as part of an improved management system that appreciably reduced NO_3^- leaching and N fertiliser use. Subsequent studies, in this system, suggested that sufficiency values may be lower (R. B. Thompson, unpublished data). Through replication and careful selection of representative locations, the average coefficients of variation (CV) of measurements of soil solution [NO_3^-] reported by Granados et al. (2013) were relatively low, being only 27%. Without careful selection of representative sites in the same greenhouse system (e.g. avoiding where rainfall entered the greenhouse), CV values were appreciably higher (Granados, 2011). These observations suggest that the high spatial variability reported by Hartz (2003) can be reduced by increasing the number of replicates and by careful site selection.

Small portable “quick test” systems (Parks et al., 2012; Thompson et al., 2009) enable on-farm determination of the [NO_3^-] in samples of soil solution. With rapid analysis systems, considerable care must be taken and results should be periodically checked against laboratory analysis. Combining the use of the suction samplers with on-farm analysis with "quick test" systems enables rapid assessment of the immediately available N supply in the root zone.

Ceramic cup suction soil solution samplers appear to be a useful approach for identifying excessive N fertilisation of fertigated vegetable crops through the observation of tendencies of increasing soil solution [NO_3^-]. Given the current uncertainties associated with definition of sufficiency ranges and the issue of spatial variability of soil solution [NO_3^-], it is suggested that other approaches (e.g. crop/plant testing) be used to accurately determine N insufficiency. As a general rule for the use of soil solution [NO_3^-], with values of >5 mmol L^{-1}, in the immediate root zone, it is unlikely that the immediate N supply will limit crop growth.

3.9. Use of limits of residual soil mineral N

In the region of Flanders in Belgium, there is a legal limit on the amount of residual soil mineral N in the autumn/early winter period after open field cropping (S. de Neve, University of Ghent, Belgium, personal communication). The limit is 90 kg N ha^{-1} in 0-90 cm soil; samples are taken between 1 October and 15 November. If there is >90 kg N ha^{-1}, growers are penalised.

With the increasingly strict implementation of legislation to reduce contamination of water bodies with N from agriculture, this approach may be implemented elsewhere. It is one of the few means by which the net result of a grower's management can be evaluated. However, care should be exercised when interpreting residual soil mineral N data, as they are the result of numerous interacting factors including climatic conditions.

3.10. General observations on soil testing approaches

Most of the methods based on soil analysis or soil N supply require sampling of soil or the soil solution and subsequent analysis. Soil sampling requires firstly an extraction procedure, which is generally conducted with water, or with potassium chloride or calcium chloride solutions, and subsequently requires analysis of the extractant solution. Quick test procedures, such as those described by Thompson et al., (2009) and Parks et al. (2012) can be used (e.g. He et al., 2007), but given that extraction will normally be conducted in a laboratory, laboratory analysis can also be conducted which is more accurate and reliable than quick test procedures.

A fundamental issue with soil analysis is the willingness of growers to take soil samples and to pay for analysis. Experience in Germany has been that growers are generally reluctant to take samples. Often, the limiting factor is not costs, but the difficulty to integrate the whole process associated with sampling (timely sampling, sample preparation, sending the sample to the laboratory, calculating fertiliser demand based on the analysis) into the typically hectic daily routine on a vegetable farm. However, it has been seen that growers were more motivated when the costs of the analyses were subsidised (K, Rather, State Horticultural College and Research Institute, Heidelberg, Germany, personal communication). In The Netherlands, growers in high technology greenhouses regularly use the 1:2 soil:water extract method during a crop (W. Voogt, Wageningen University & Research, The Netherlands, personal communication). It appears in these high technology production systems where growers are accustomed to a high level of monitoring, that they are willing to regularly sample soil and to pay for the analyses. It appears that grower reluctance to sample soil and to pay analysis can be at least partially overcome by increasing their technical knowledge. The provision of efficient support services to rapidly conduct analyses and provide recommendations is essential. The imposition of recommended practices through legislation will contribute to increasing adoption of soil testing approaches.

4. Nitrogen balance method

The determination of N fertiliser application rate using N balance calculations generally considers all major N inputs, thereby ensuring that the most significant N sources are considered when determining mineral N fertiliser recommendations. Essentially, the N balance subtracts the supply of N (from sources other than mineral fertiliser) from the crop demand for N; the difference being the amount of mineral N fertiliser required. Traditionally, the N balance has been calculated for the duration of a crop, resulting in an estimation of the total amount of N to be applied as fertiliser. With the use of computer-operated Decision Support Systems (DSS; see Section 8 of this chapter), N fertiliser requirements can be calculated daily or weekly using a N balance approach enabling crop, site and season specific N management. As discussed in Section 8 of this chapter, when done frequently by a DSS, these N balance calculations can be either “static”, when they are used as a fixed plan considering expected yield and average climatic conditions, or “dynamic” when a series of short-term plans are prepared with real time or forecast climatic data so that the plan is continually adapted in response to actual cropping conditions. Additional soil analyses can be used as feed-back to adjust parameters, as is done in the KNS system (Section 3.2 of this chapter) which is essentially a simplified N balance method.

The inputs and outputs considered in the N balance are listed in table 2. For each given time period, the sum of N inputs equals the sum of N outputs. Variations exist on the individual terms used in N balance calculations, and on the approaches used to solve the calculation of the N_{fert} term (e.g. Gianquinto et al., 2013; Meisinger et al., 2008;

Tremblay et al. 2001). For example, the general N losses term (N_{loss}) in table 2 can be fully expressed as the various N loss pathways of NO_3^- leaching, denitrification and NH_3 volatilisation, plus immobilisation. Estimating each N loss pathway is very difficult given the dynamic nature of each pathway, the difficulties of measurement, and the shortage of reliable field data. Consequently, a generalised N loss term is commonly used, as in table 2. Two or all three of the N mineralisation terms may be combined. The German N-Expert system, another method based on the N balance (see Sections 3.3 and 8.2 of this chapter), combines all N mineralisation terms and the general N losses term into the term Apparent Nitrogen Mineralisation which is the combined N mineralisation from all sources minus all N losses and immobilisation. Depending on site management and history, some N input terms will not be relevant, e.g. if manure or irrigation are not used.

Table 2. N inputs and outputs considered for developing a N balance. Note: the subscript "min" refers to mineral N and the subscript "mins" to mineralised N

N Inputs	**N Outputs**
Initial soil mineral N ($N_{min\text{-}ini}$)	Crop N (N_{crop})
N mineralised from soil OM ($N_{mins\text{-}OM}$)	N losses (N_{loss})
N mineralised from crop residues ($N_{mins\text{-}crop\ res}$)	Final soil mineral N ($N_{min\text{-}fin}$)
N mineralised from manure ($N_{mins\text{-}man}$)	
N applied in irrigation (N_{irr})	
Mineral N fertiliser (N_{fert})	
Total N Inputs ($\sum$Inputs)	Total N Outputs ($\sum$Outputs)

As previously mentioned, there are variations between authors in the details of N balance calculations and of the terms and approach used. However, a consistent feature is that all major N sources are considered. There are two main approaches: (1) the efficiency factor approach, or (2) the safety margin approach. With the efficiency factor approach, the N_{loss} and $N_{min\text{-}fin}$ terms are removed and instead are implicitly considered by either applying efficiency factors to each of the N inputs considered (Gallardo et al., 2014; Meisinger et al., 2008) or by the use of a single efficiency factor for the combined N inputs (Thompson et al., 2013a) as in equation 6.

$$N_{fert} = (1/E) * [N_{crop} – (N_{min\text{-}ini} + N_{mins\text{-}OM} + N_{mins\text{-}res})] \qquad \text{Eq. 6}$$

where E is the efficiency of use N supplied to the crop, and $N_{mins\text{-}res}$ is the combination of $N_{mins\text{-}crop\ res}$ and $N_{mins\text{-}man}$ (Table 2).

Given the difficulty of obtaining reliable efficiency factors, the “safety margin” approach is a practical alternative (Gianquinto et al., 2013; Tremblay et al., 2001), and is used in practical manuals prepared for farmers and advisors (e.g. Tremblay et al., 2001). The safety margin is the equivalent of the buffer soil mineral N defined for the KNS system (Section 3.2 of this chapter), which is the minimum amount of soil mineral N that must be present in the root zone to avoid a yield reduction. Tremblay et al. (2001) used the equation:

$$N_{fert} = (N_{crop} + N_{Safety\ margin} + N_{Immobilisation}) – (N_{min\text{-}ini} + N_{mins\text{-}OM} + N_{mins\text{-}crop\ res}) \qquad \text{Eq. 7}$$

where $N_{Safety\ margin}$ is the safety margin or buffer amount of soil mineral N and $N_{Immobilisation}$ is an estimate of immobilisation calculated as (N_{crop} + $N_{Safety\ margin}$) x 0.15.

Tremblay et al. (2001) used equation 7 for various species and scenarios under the conditions of Germany, and Quebec, Canada. In doing so, $N_{mins\text{-}OM}$ was assumed to be 5 kg N ha^{-1} week^{-1} for these conditions (similar to the value assumed by the KNS system described in Section 3.2 of this chapter), and formulas were provided to calculate $N_{mins\text{-}crop\ res}$. N_{crop} (for the entire crop) can be estimated by multiplying expected yield by N uptake per unit of yield. Tabulated values of the latter were provided by Tremblay et al. (2001) for common vegetable crops in Germany and Canada, and by Gianquinto et al. (2013) for the Mediterranean Basin. Commonly, local values are available.

Gianquinto et al. (2013) presented a simplified practical solution of the N balance. Firstly, N_{crop} is estimated by multiplying expected yield by N uptake per unit of yield. Then equation 8 is solved:

$$N_{fert} = N_{crop} - N_{min\text{-}ini} \qquad \text{Eq. 8}$$

The N_{fert} value is then adjusted to an “adjusted value of fertiliser N” ($N_{adj\text{-}fert}$) to consider the inefficiency of N fertiliser use because of N losses and residual soil mineral N. This is done using either: the (a) efficiency factor approach (equation 9) or (b) safety margin approach (equation 10) that were described previously.

$$N_{adj\text{-}fert} = N_{fert}/E \qquad \text{Eq. 9}$$

$$N_{adj\text{-}fert} = N_{fert} + N_{Safety\ margin} \qquad \text{Eq. 10}$$

5. Methods based on crop/plant analysis

5.1. Crop and plant monitoring approaches – General considerations

Monitoring of crop or plant N status potentially integrates crop N demand and the soil N supply, providing an overall assessment of whether the two are in balance or not (Schröder et al., 2000). Imbalances can occur despite an apparently adequate soil N supply, such as when very rapid crop N uptake follows measurement of soil mineral N, when there is very low N supply in the immediate root zone, or the crop has a poorly developed root system. Many of the more recent crop/plant N monitoring approaches enable rapid *in-situ* assessment of crop N status. Supplementing soil analyses with crop/plant monitoring could provide a comprehensive assessment of the N status of a given crop. Important issues when dealing with crop/plant monitoring approaches are the interpretation of the results, firstly to inform users of whether a crop has deficient, sufficient or excessive N status, and secondly the transformation of the results into fertilizer recommendations. These comments are relevant to the monitoring methods based on crop/plant analysis described subsequently in this Section, and those using proximal optical sensors described in Section 6.

5.2. Tissue analysis

Measurement of leaf N content, also known as N tissue analysis, is a long established method of assessing crop N status (Burt et al 1995; Geraldson and Tyler, 1990; Hartz and Hochmuth, 1996). Most commonly, the most recently fully expanded leaf is sampled. Generally, sufficiency ranges (with maximum and minimum values) for different phenological phases are used to interpret the results, with a progressive reduction in sufficiency ranges with crop growth as the crop N content declines (e.g. Hartz and Hochmuth, 1996; Hochmuth, 2012). Hartz and Hochmuth (1996) and

Hochmuth (2012) published values of sufficiency ranges for numerous vegetable species grown in Florida, USA; Hartz and Hochmuth (1996) suggested that sufficiency ranges for crops grown California are likely to be similar. In general, it is preferable that locally-determined sufficiency ranges and values be used. For example, in Almeria, SE Spain, Casas and Casas (1999) determined local reference values for a range of greenhouse-grown vegetable species.

There are mixed reports of the nature of the relationships between leaf N with overall crop N content and crop status. Leaf N content was strongly and consistently correlated with total crop N content (Bottoms et al., 2012; Peña-Fleitas et al., 2015) throughout tomato crops suggesting that leaf N content can be used as a surrogate of crop N content. However, the correlation was not consistent over time in muskmelon (Peña-Fleitas et al., 2015) or lettuce (Bottoms et al., 2012). Peña-Fleitas et al. (2015) observed on-going changes in the relationship of leaf N content with crop N status, assessed using the Nitrogen Nutrition Index (NNI; Lemaire et al., 2008) in tomato and muskmelon, which is consistent with the reduction in sufficiency values with crop growth. The NNI is an effective and established indicator of crop N status (Lemaire et al., 2008; Padilla et al., 2014; 2015; 2016). The NNI is the ratio between actual crop N content and the critical crop N content (i.e. the minimum N content necessary to achieve maximum growth of a crop) (Greenwood et al., 1990). Values of NNI of <1 indicate N deficiency, values of >1 indicate N excess, and values of ≈1 indicate N sufficiency (Lemaire et al., 2008).

Olsen and Lyons (1994) reported that leaf N is a relatively insensitive measure in sweet pepper because of its limited response to short-term periods of inadequate N supply. This insensitivity was attributed to there being only relatively small changes in leaf protein which constitutes most of the leaf N content (Olsen and Lyons, 1994). The availability of suitable sufficiency values is an important consideration. Sufficiency values for a given species may vary with differences in climate, region, crop management and cultivar. Where local sufficiency values are not available, they should be determined or values from a similar cropping system and region should be validated before being recommended. Practical considerations are the logistics of sending samples to a laboratory, the time delay to obtain results, and the cost of laboratory analyses. For routine testing, it appears to be best suited to where infrequent side-dress N applications are made. Given its relative unresponsiveness and the time delay to obtain results, it is not suitable for frequent N application with fertigation.

5.3. NO_3^- analysis of dried petiole or mid-rib tissue

Nitrate analysis of dried petiole or mid-rib tissue has been available for a number of years (Burt et al., 1995; Goffart et al., 2008). Burt et al. (1995) published detailed tables of sufficiency values for numerous vegetable species for the USA. Inconvenient aspects are the time to obtain the samples and to obtain laboratory results. In recent years, there has been little work on this method.

5.4. Petiole sap NO_3^- analysis

Petiole sap NO_3^- analysis measures the $[NO_3^-]$ in the conducting tissue of leaf petioles, and is considered to be a sensitive indicator of crop N status at the time of sampling (Burt et al., 1995; Goffart et al., 2008; Olsen and Lyons, 1994). The sensitivity of sap $[NO_3^-]$ to crop N status has been demonstrated in various vegetable crops, including processing tomato (Farneselli et al., 2014; Hartz and Bottoms, 2009), pepper (Olsen and Lyons, 1994) and potato (Goffart et al., 2008).

Normally, the most recent fully expanded leaf is sampled; it is recommended that >20 petioles be sampled from different representative plants to overcome variation between individual plants (Goffart et al., 2008). Strict protocols need to be followed for leaf selection, petiole removal, handling and storage, and for the extraction and storage of sap samples (Farneselli et al., 2006; Hochmuth, 1994; 2012). Analysis can be made on farm using small portable rapid analysis systems (Hochmuth, 1994; 2012; Parks et al., 2012; Thompson et al., 2009), some of which can measure sap [NO_3^-] without dilution. With rapid analysis systems, considerable care must be taken with the calibration, use of and maintenance of the equipment, and results should be periodically checked against laboratory analysis.

Most reports are that the petiole sap [NO_3^-] declines notably as crops grow (e.g. Hartz and Bottoms, 2009; Hochmuth, 1994; 2012). Recommendations are generally made as sufficiency ranges for phenological phases; the reported sufficiency ranges commonly decline as crops grow and develop (e.g. Hochmuth, 1994; 2012). However, in tomato and muskmelon grown in soil in a greenhouse and which received N every 1–4 days in complete nutrient solutions through a combined fertigation/drip irrigation system, petiole sap [NO_3^-] remained relatively constant for each of four different treatments in which different applied N concentrations were maintained throughout the crops (Peña-Fleitas et al., 2015) (Figure 3). Farneselli et al. (2014) did not observe a constant decline in sap [NO_3^-] of fertigated open field tomato, whereas Hartz and Bottoms (2009) did. These results suggest that fertigated vegetable crops receiving very frequent N applications may not exhibit the appreciable decline in sap [NO_3^-] that has been commonly reported for crops receiving pre-plant and side-dress N applications. This may be related to the observation of Goffart et al. (2008) that individual N applications and the form of N can influence sap [NO_3^-]. Further work is required to elucidate the evolution of sap [NO_3^-] in fertigated vegetable crops and to explain the different general tendencies reported by Peña-Fleitas et al. (2015) and Farneselli et al. (2014) compared to Hartz and Bottoms (2009).

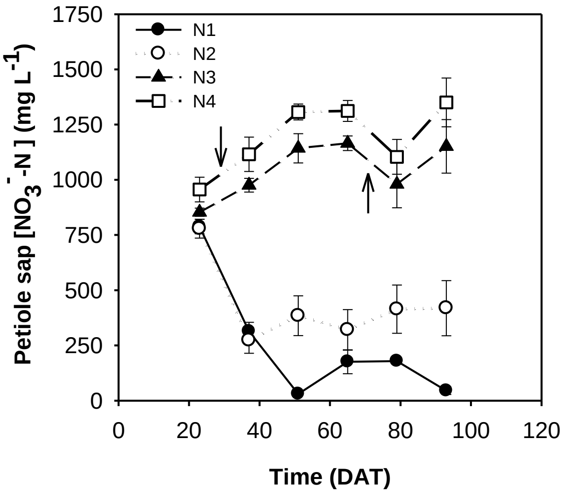

Figure 3. Petiole sap [NO_3^-] during a fertigated tomato crop grown in a greenhouse in SE Spain. The average applied N concentration was 1, 5, 13 and 22 mmol L^{-1} for treatments N1, N2, N3 and N4, respectively. Values are means ± SE (n=4). Arrows in each graph indicate the commencement of N treatments (↓) and the day of topping (↑). DAT is days after transplanting. Reproduced with permission from Peña-Fleitas, T., Gallardo, M., Thompson, R.B., Farneselli, M., Padilla, F.M. (2015) Assessing crop N status of fertigated vegetable crops using plant and soil monitoring techniques, Annals of Applied Biology 167, 387-405, published by John Wiley and Sons.

Peña-Fleitas et al. (2015) obtained a very strong linear relationship between sap [NO_3^-] and NNI (described in Section 5.2 of this chapter) for an indeterminate tomato crop grown with fertigation in a greenhouse (Figure 4). Re-analysing data of Farneselli et al. (2014) of two field-grown determinate tomato crops, Peña-Fleitas et al. (2015) obtained nearly identical linear relationships between sap [NO_3^-] and NNI as was obtained for the greenhouse-grown tomato crop (Figure 4). Using a common linear relationship for these three tomato crops (Figure 4), Peña-Fleitas et al. (2015) derived a unique sufficiency value of 1050 mg L^{-1}, for NNI = 1, for the three tomato crops. In greenhouse-grown, fertigated muskmelon there was also a relatively constant and strong linear relationship between sap [NO_3^-] and NNI throughout much of the crop (Peña-Fleitas et al., 2015). The strong linear and relatively constant relationships with NNI observed in these crops, suggest in fertigated vegetable crops, that sap [NO_3^-] is a sensitive indicator of crop N status. Further work is required to explore the relationship between sap [NO_3^-] and crop N status in fertigated crops.

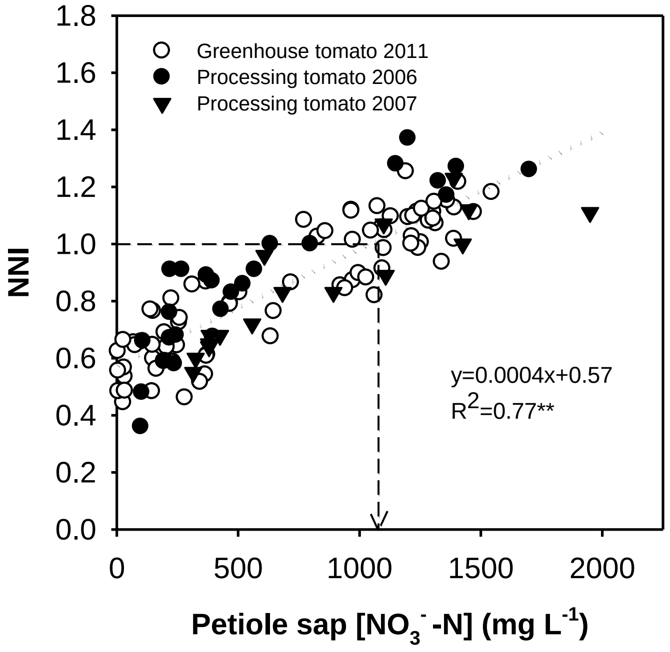

Figure 4. Linear relationship of petiole sap [NO_3^-–N] to Nitrogen Nutrition Index (NNI) for tomato combining all data from a greenhouse-grown, indeterminate, fresh market tomato crop in 2011 (Peña-Fleitas et al., 2015) and from two determinate, processing tomato crops grown in open fields in 2006 and 2007 (Farneselli et al., 2014). Data excluded in processing tomato were from the first sampling date at 30 days after

transplanting (DAT) in both the 2006 and 2007 crops and from the last sampling dates of 84 DAT in 2006 and of 71 and 84 DAT in 2007 (see Peña-Fleitas et al. (2015). The derivation of a general sufficiency value of 1050 mg NO_3^-–N L^{-1} that corresponds to NNI = 1 is shown. Reproduced with permission from Peña-Fleitas, T., Gallardo, M., Thompson, R.B., Farneselli, M., Padilla, F.M. (2015) Assessing crop N status of fertigated vegetable crops using plant and soil monitoring techniques, Annals of Applied Biology 167, 387-405, published by John Wiley and Sons.

As a general assessment, petiole sap NO_3^- analysis can provide useful information on the N status of vegetable crops. However, petiole sap [NO_3^-] values can be affected by factors such as cultivar, amount and timing of N previous application, crop water status and of rainfall events stimulating N mineralisation (Goffart et al. 2008). It has been demonstrated that petiole sap [NO_3^-] is a good indicator of crop N status for a given vegetable species in a given region, e.g. processing tomato in central Italy (Farneselli et al., 2014). In general, it appears that sap [NO_3^-] can potentially provide information on the adequacy of crop N status for a given species within a given region, and that consistent N management practices (e.g. timing, pre-plant applications) and similarity of cultivars and general crop management are likely to improve its viability both within and between regions. Recent results with fertigated vegetable crops suggest that frequent N and irrigation application (Peña-Fleitas et al., 2015) may reduce the influence of crop management and climatic factors such that similar sufficiency values can be used with the same species in different regions.

As with all crop/plant monitoring procedures to assess N crop status, the issues of (a) detecting excess crop N status and (b) relating measurements to fertiliser recommendations have generally received insufficient attention and require further work.

6. Use of proximal optical sensors

There has been a tremendous amount of recent research with proximal optical sensors to assess crop N status and to assist in determining N fertiliser application rates for various agricultural crops (e.g. see reviews by Fox and Walthall, 2008; Samborski et al., 2009; Tremblay et al., 2012). Proximal sensors are a form of remote sensing in which the sensors are positioned either in contact or close to the crop. These sensors do not directly measure N content in plant tissue, but provide measurements of optical properties that are indicative of crop N status, thereby indicating N sufficiency or the degree of N deficiency. The issue of detecting N excess with crop monitoring approaches is discussed in Section 7 of this chapter. Measurements with proximal optical sensors can be made quickly and periodically throughout a crop; and the results are usually very rapidly available. Some sensors are limited to individual spot measurements while others have continuous "on-the-go" capabilities that enable large representative surface areas of foliage to be measured and mapped.

To date, most of the evaluations of proximal optical sensors have been with cereals for single N fertiliser applications at a given crop development stage or age. For vegetable crops, more frequent assessment will often be warranted such as when N is applied frequently by fertigation. A key issue for the use of proximal optical sensors, as with all forms of crop monitoring, is the requirement for sufficiency values or ranges (as defined in Section 2 of this chapter). For practical use in vegetable production, where planting dates and cropping cycles can vary appreciably, sufficiency values or ranges should be related to phenological stages or thermal time. The effects of different cultivars or classes of cultivars need to be assessed.

6.1. Interpretation of data from proximal optical sensors

Proximal optical sensors measure optical properties of plants, such as light transmittance, canopy reflectance or chlorophyll fluorescence. Sensor measurements usually involve 2–3 simultaneous measurements of a property at different wavelengths, which are integrated using equations known as vegetation indices. To relate sensor measurements or indices to crop N status, a calibration or normalisation procedure is required. Two broad approaches are used: (a) absolute values related directly to crop N status, and (b) Sufficiency Index (SI) values. The use of absolute values can be based on yield response functions (Fox and Walthall, 2008; Gianquinto et al., 2004) or directly related to measures of crop N status such as the Nitrogen Nutrition Index (NNI; described in Section 5.2 of this chapter) (Mistele and Schmidhalter, 2008; Padilla et al., 2015; 2016) or to crop or leaf N content (e.g. Chen et al., 2010; Gianquinto et al., 2011a; Padilla et al., 2014; 2015).

In the SI approach, the sensor measurement or derived vegetation index from each crop is divided by a measurement or equivalent index value obtained from a small area of the same crop (N reference plot) managed so that N is not limiting (Samborski et al., 2009; Tremblay and Bélec, 2006; Tremblay et al., 2011). The rationale of the SI approach is that effects of various factors on optical measurements, that are common to both the measured area and the N reference plot, such as abiotic and water stress, disease incidence and cultivar are normalised, thereby isolating the difference in N status (Samborski et al., 2009; Tremblay and Bélec, 2006). The SI approach provides a relative value that indicates the degree of N deficiency; it enables such assessment to be made at different growth stages and with different cultivars. Sufficiency Index values that have been recommended for different crops in different locations, generally range from 0.90 to 0.96 (Samborski et al., 2009). These SI values represent sufficiency values; lower values are regarded as indicating that N fertiliser application is required. An alternative to the establishment of a non-N limiting reference plot is the virtual-reference concept (Holland and Schepers, 2013) where an area within the field with good growth is assumed not to be N limited and is used as a reference. The SI approach assumes that there is a plateau response due to sensor saturation when N is not limiting, because either (a) luxury N uptake does not occur or (b) if luxury N uptake does occur, it will not be reflected in a saturated sensor reading.

It is commonly regarded that the plateau response occurs. However, differences between vegetable species have been reported (see Section 7 of this chapter); appreciable luxury N uptake reflected in sensor readings occurred in muskmelon (Padilla et al., 2014) but was moderate in cucumber (Padilla et al., 2016). Where luxury N uptake occurs and sensor readings do not saturate, the SI approach will not be suitable. The issue of luxury N uptake and crop monitoring is discussed more fully in Section 7.

Where the SI approach is not suitable, an alternative procedure is required to relate the absolute values measured by the sensor to crop N status. Padilla et al. (2015) reported a procedure to determine sufficiency values for absolute values of optical sensor readings, with vegetable crops, that can be used to derive sufficiency values for frequent measurement (e.g. each 1–2 weeks) and for individual phenological phases. This procedure is based on the relationships between optical sensor measurements and NNI. Procedures to relate absolute values measured directly by the sensor to crop N status have to consider issues such as standardisation of tissue measured, selection of crop growth stages, and the various possible issues that are normalised when using the SI approach.

Where deficient crop N status is identified, the N fertiliser requirement must be determined. The N fertiliser requirement can be quantitatively and directly related to SI values or to absolute sensor readings by use of an algorithm (e.g. Holland and Schepers, 2013; Solie et al. 2012) or this can be done semi-quantitatively by making adjustments to a previous plan of N fertiliser applications.

6.2. Chlorophyll meters

Chlorophyll meters (CMs) are small, hand-held, clip-on optical sensors that indirectly measure leaf chlorophyll content. Leaf chlorophyll content is correlated to leaf N content (Fox and Walthall, 2008). There are currently several commercially available sensors, including the SPAD-502 (Konica-Minolta, Japan) and Hydro N-tester (Yara International, Norway) which are almost identical, and the more recent atLeaf sensor (FT Green LLC, DE, USA; Zhu et al., 2012) and Apogee chlorophyll meter (Apogee Instruments, Inc., UT, USA; Parry et al., 2014). The atLeaf sensor is much cheaper than the established SPAD-502 and Hydro N-tester sensors. Most research work has been done with the SPAD-502. Chlorophyll meters generally measure leaf chlorophyll content in their own units (SPAD, HNT or atLeaf units); the Apogee CM measures in µmol of chlorophyll per m^2 of leaf surface or in SPAD units. For each individual measurement, the measured area is generally <10 mm^2. Consequently, there is a requirement for appreciable replication e.g. 20–40 measurements on different plants per field or experimental treatment, and for strict measurement protocols (e.g. leaf selection, position on leaf).

Chlorophyll meters such as the SPAD and N-tester estimate leaf chlorophyll by the differential transmission of red and near infra-red (NIR) radiation (Figure 5).

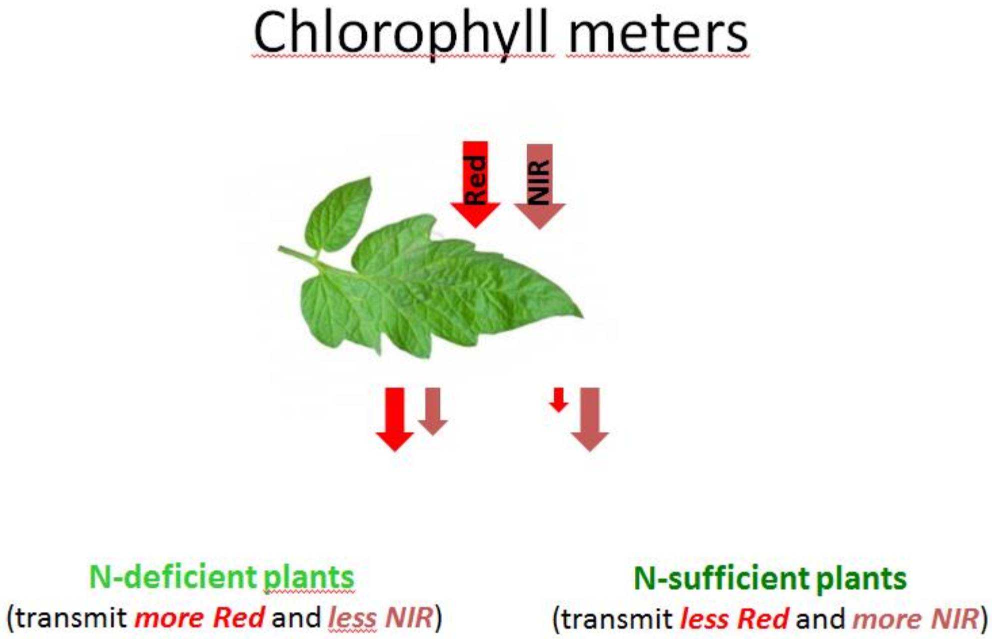

Figure 5. Schematic representation of the differential transmission of red and infra-red light used to estimate leaf chlorophyll content with leaf chlorophyll meters.

There are many research publications on the use of CM to evaluate crop N status, mostly with field crops, which have been reviewed by Fox and Walthall (2008), Goffart et al. (2008), Meisinger et al. (2008), and Samborski et al. (2009). These reviews also describe general interferences, protocols and data interpretation. A number of studies have been done with various vegetable species and potato (e.g. Farneselli et al., 2010; Gianquinto et al., 2006; 2011b; Goffart et al., 2008; Padilla et al. 2014; 2015; Westerveld et al. 2004). The variety of leaf forms of vegetable species has implications for CM measurement. For example, finely-dissected leaves of carrot can be difficult to measure and leaf veins must be avoided (Westerveld et al. 2004). Composite (e.g.

tomato) and large leaves (e.g. melon, cucumber) require well-defined and consistent measurement points as considerable variability in readings can occur within leaves.

Numerous studies with different vegetable species have generally reported significant relationships between CM readings and crop/leaf N content or crop NNI for given sampling times throughout a crop. These relationships differ between species and change during a given crop (e.g. Gianquinto et al., 2006; 2011b; Padilla et al., 2014; 2015). Relationships between CM readings and crop N status are generally linear (Gianquinto et al., 2006; Padilla et al., 2014; 2015; Zhu et al., 2012); sometimes plateau responses occur at relatively high N contents, suggesting saturation (e.g. Goffart et al., 2008). It is not clear exactly what are the conditions (e.g. species, chlorophyll and N contents) when saturation occurs; this requires further elucidation. Protocols for using CMs to aid vegetable crop N management have been developed (Gianquinto et al., 2004; 2011b; Olivier et al., 2006; Samborski et al., 2009). CM sensors are robust, sensitive and easy to use; however, despite this and the considerable amount of research conducted with CMs, there appears to have been little adoption into crop N management with vegetable or other types of crops. Problems include lack of sensitivity and specificity, the intensity of the sampling effort needed, and the absence of stable relationships with actual N fertiliser requirements.

6.3. Reflectance sensors

There has been substantial recent research on the use of proximal reflectance sensors to assist with crop N management (e.g. Fox and Walthall, 2008; Meisinger et al., 2008; Samborski et al., 2009; Schmidt et al, 2009; 2011). These optical sensors are commonly positioned 0.4–3.0 m from the crop canopy. Much of the recent research has been conducted with cereal crops where they are used commercially to control variable rate application of N fertiliser (Fox and Walthall, 2008; Meisinger et al., 2008; Samborski et al 2009). Most, particularly the newer reflectance sensors, are active sensors e.g. the various Crop Circle (Holland Scientific, Inc, Lincoln, NE, USA), and Greenseeker sensors (Trimble Navigation Ltd., Sunnyvale, CA, USA), and the Yara N Sensor ALS (Yara International ASA, Oslo, Norway) have their own light source so that they can be used in any light conditions. Many reflectance sensors can be mounted on a tractor to automatically control N fertiliser application rates; most can be used for manual measurement. Both the Crop Circle and Greenseeker ranges have simpler, cheaper, hand-held models that are well-suited to manual use with vegetable crops.

A big advantage of proximal reflectance sensors is that because of their on-the-go capabilities they can measure large representative areas of the crop canopy. Canopy reflectance measurements are based on the interaction of different light wavelengths, in the visible and near infra-red (NIR) spectrum, with the crop canopy. This interaction is influenced by crop N status (Fox and Walthall, 2008; Samborski et al., 2009). The reflectance of 2–3 individual wavelengths such as green, red, far-red, and NIR are used in mathematical equations to derive vegetation indices. Among the numerous indices that have been proposed, the most commonly-used is the NDVI (Normalised Difference Vegetation Index). A detailed list of relevant indices and their calculation is provided by Bannari et al. (1995) and by Li et al. (2010). Commonly, the selected indices are interpreted for N management using the Sufficiency Index (SI) discussed in Section 6.1 of this chapter, or by establishing relationships with measures of crop N status such as the Nitrogen Nutrition Index (Mistele and Schmidhalter, 2008; Padilla et al., 2015). A schematic representation of the differential reflectance of visible and near-infra red radiation used to calculate reflectance indices is presented in Figure 6.

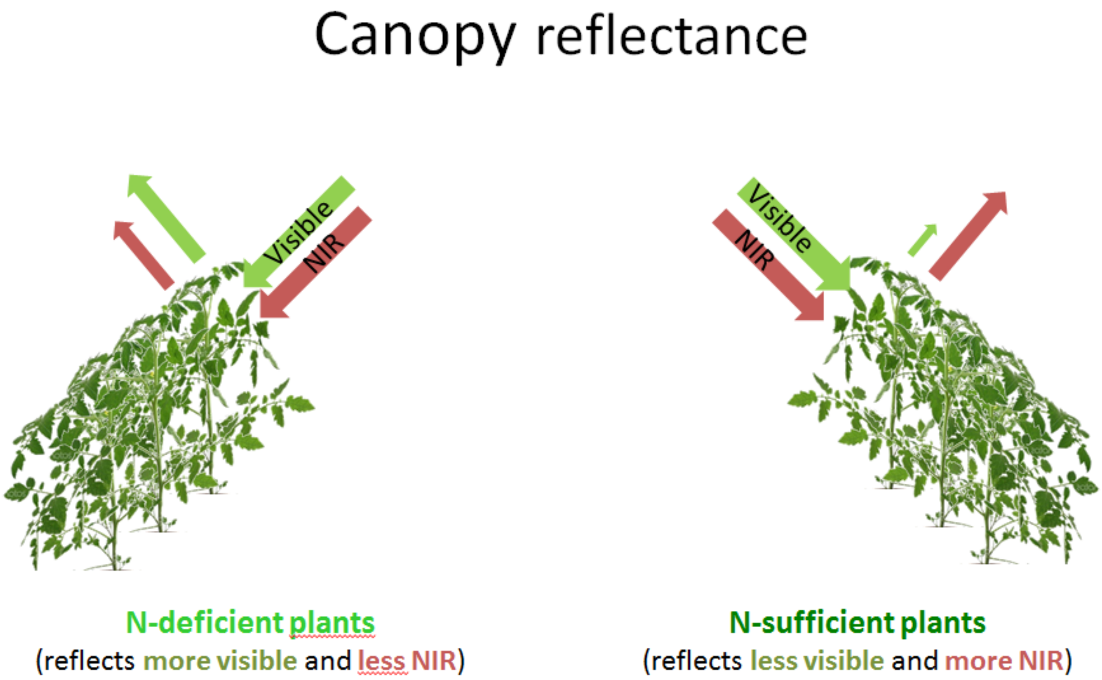

Figure 6. Differential reflectance of visible and near-infra red radiation used to calculate vegetation indices with canopy reflectance sensors.

For vegetable crops, studies with tomato (e.g. Gianquinto et al., 2011a; Padilla et al., 2015), muskmelon (Padilla et al., 2014) and cucumber (F.M. Padilla, unpublished data; Wei et al., 2010) have demonstrated the sensitivity of canopy reflectance measurements throughout crops. As yet, unlike with cereals, there appears to be little use of canopy reflectance sensors for N fertiliser management in commercial vegetable production.

6.4 Fluorescence measurement of polyphenols

Polyphenolic compounds, in particular flavonols are produced in plant leaves particularly under stress conditions so that their content is usually inversely related to crop N status. The ratio of chlorophyll to flavonols (or polyphenols), known as the Nitrogen Balance Index (NBI) has been reported to be very sensitive to crop N status, as chlorophyll decrease and flavonols (or polyphenols) increase when N becomes limiting (Padilla et al., 2016;Samborski et al., 2009; Tremblay et al., 2009; 2012). Optical sensors based on measurement of fluorescence properties have been developed to estimate the contents of both flavonols (or polyphenols) and chlorophyll. The two most-commonly used fluorimeters for are the DUALEX4-FLAV which is a clip-on sensor and the MULTIPLEX which is a proximal sensor, both are produced by Force-A, Orsay, France.

The measurement principle used by these sensors is that mesophyll chlorophyll emits fluorescence in the red to far-red region of the light spectrum after being illuminated with ultraviolet (UV) and red light. Flavonols that accumulate in the leaf epidermis absorb appreciable amounts of UV light while transmitting most of the red light; the transmitted red light is subsequently absorbed by the chlorophyll in mesophyll chloroplasts. Flavonols reduce far red chlorophyll fluorescence under UV illumination without altering far red chlorophyll fluorescence under red illumination, so the flavonols content is estimated by comparing far red chlorophyll fluorescence under red and UV wavelengths (Figure 7).

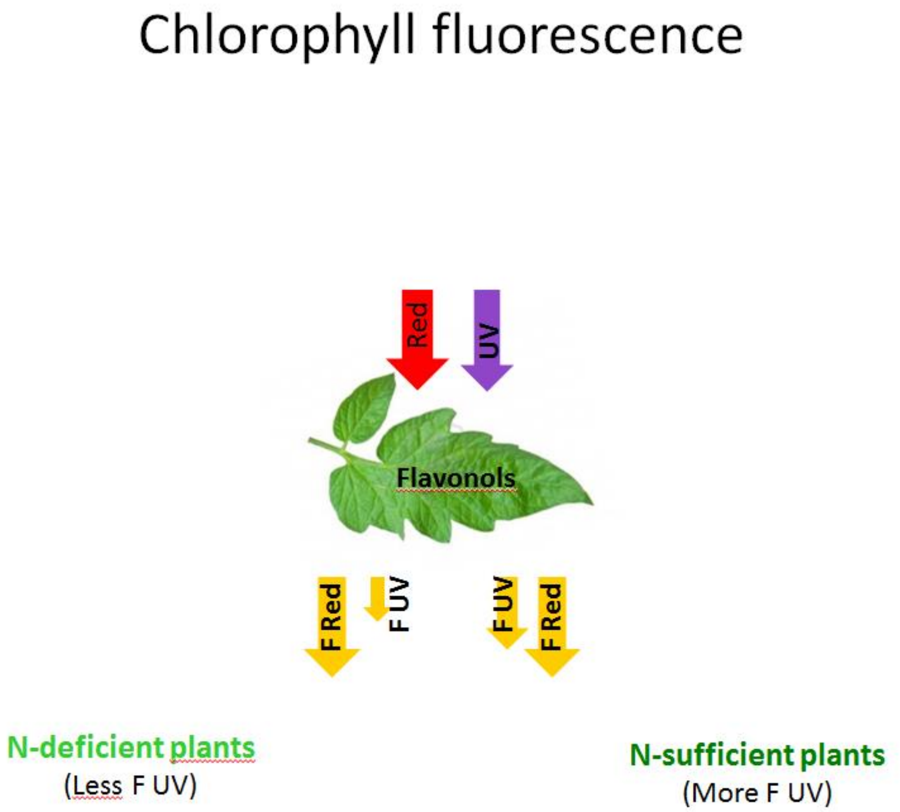

Figure 7. Schematic representation of the differential emission of chlorophyll fluorescence under red and UV wavelengths that is used to estimate leaf flavonols content. “F” refers to fluorescence.

A number of studies have suggested that leaf flavonols and the ratio of chlorophyll to flavonols (NBI) are earlier, more sensitive and more specific indicators of crop N status (Tremblay et al., 2009; 2012) than chlorophyll estimation. Padilla et al. (2014; 2016) reported that these measurements were sensitive to crop N status in muskmelon and cucumber, respectively. This is a relatively recent and promising line of research.

6.5 Hyperspectral proximal sensors

In recent years, there has been an increased availability of, and interest in the use of, high resolution hyperspectral (HS) field radiometers. Hyperspectral proximal sensors measure reflectance in small wavelength intervals across a broad and nearly continuous spectrum, including the visible (400–700 nm), NIR (700–1350 nm) and short wavelength infrared (1350–2500 nm) ranges. This provides the potential for appreciable improvement of the assessment of biophysical and biochemical characteristics of agricultural crops compared to canopy reflectance sensors that measure only a small number of pre-selected wavelengths (Jain et al., 2007; Thenkabail et al., 2012). The use of indices that exploit reflectance measurements in narrowband intervals, especially those involving the red-edge region, have produced good results in characterising plant nutrient status (Perry and Roberts, 2008; Thenkabail et al., 2012). Although promising results have been observed in studies combining multivariate analysis of HS data and field mapping of plant characteristics, their transformation into fertiliser recommendations requires more research particularly for vegetable crops where little research work has been conducted. Moreover, in their current formats, hyperspectral proximal sensors require intensive data processing after field measurement, which appreciably diminishes their utility for practical use. The integration of HS data with crop simulation models is a promising approach to optimise N management (Baret et al., 2007).

7. Luxury N consumption and responses of monitoring approaches at excessive crop N status

Given that excessive N application is a common occurrence in intensive vegetable production, the ability of plant/crop monitoring approaches to detect excessive N supply is an important practical consideration. Under excessive N supply, the amount of N taken up by the crop can exceed the minimum amount necessary to achieve maximum growth (the critical N uptake amount) resulting in luxury N uptake (Lemaire and Gastal, 1997). There appears to be differences among vegetable species in the occurrence of luxury N uptake, and, where it does occur, in the degree of luxury N uptake. Appreciable and moderate luxury N uptake was observed in muskmelon (Padilla et al., 2014) and cucumber (Padilla et al., 2016), respectively. The EU-Rotate_N model considers that there are differences among species in the occurrence and degree of luxury N uptake (Rahn et al., 2010). Of the 32 vegetable crops considered by the EU-Rotate_N model, 18 are indicated as having varying degrees of luxury N uptake, and 14 as not having luxury N uptake (Rahn et al., 2010). These assessments of luxury N uptake were based on a mixture of experience and agronomic trials (C. Rahn, University of Warwick, United Kingdom, personal communication).

Species that have little or no luxury N uptake will not accumulate appreciable additional N once N sufficiency has been achieved even when increasingly excessive N is applied. In species, where little or no luxury N uptake occurs, monitoring approaches related to crop N content will generally not be able to distinguish excessively fertilised from adequately N fertilised crops. In such species, the Sufficiency Index (described in Section 6.1 of this chapter), which assumes that measurements exhibit a plateau response with an increasingly excessive N supply after N sufficiency, could be used to identify and characterise N deficiency.

Where luxury N uptake does occur, crop monitoring may respond to an excessive N supply. In a muskmelon crop with appreciable luxury N uptake, Padilla et al. (2014) reported that sensor readings of a chlorophyll meter and canopy reflectance indices increased with increasingly excessive N supply and crop N status. In such species, where monitoring measurements do not exhibit a plateau response when crops increasingly accumulate excessive N, the Sufficiency Index may not be suitable. Where the Sufficiency Index is not suitable, sufficiency values and ranges based directly on absolute values may be more appropriate.

It appears that there may be two factors that influence the response of monitoring approaches to excessive N supply: (1) the occurrence or not of luxury N uptake, and (2) the response of the monitoring approach to the component being measured e.g. chlorophyll readings made with a SPAD meter that saturate at very high leaf chlorophyll contents associated with very high N contents (Cartelat et al, 2005). The limited available data suggest (a) that plateau sensor responses may occur and that the mechanism maybe one or both of the factors previously mentioned, and also (b) that plateau sensor responses do not always occur (e.g. Padilla et al., 2014). Further work is required to identify and understand crops where plateau sensor responses do not occur and there may be diminishing sensor responses to increasing crop N status which could influence the sensitivity of the monitoring approach to distinguish excessive crop N status. Further discussion on the interpretation of data from optical sensors is presented in Section 6 of this chapter.

In relation to the capacity of other monitoring approaches such as tissue analysis and petiole sap analysis to detect excess crop N status, there are limited data. Where appreciable luxury N uptake does not occur or does so in a limited manner, it is unlikely that the leaf sampled for tissue analysis will respond differently to the entire plant. Therefore, in such species, it seems unlikely that tissue testing will be capable of clearly detecting excess N status. It may be able to do so in species where appreciable luxury N uptake occurs. Regarding petiole sap analysis, there are insufficient published studies with excessively fertilised vegetable crops to assess the capacity of this approach to detect excessive crop N status.

8. Use of simulation models and decision support systems for N management

For N management, simulation models can be used: (a) to estimate crop fertiliser N requirements and/or (b) for scenario analysis to demonstrate the impact of N management on crop response and N losses to the environment. Given that irrigation is commonly used in vegetable production and that fertigation is being increasingly adopted, a number of simulation models that deal with N management of vegetable also consider irrigation.

Simulation models that estimate crop fertiliser N requirements may be incorporated into user-friendly Decision Support Systems (DSSs) with the aim of providing practical tools for growers and technical advisors to develop N fertiliser plans. These DSSs consider crop N demand, usually for short time intervals throughout a crop, and other N sources, and calculate N fertiliser requirements as supplemental N required to optimise crop N status.

The use of models for scenario analysis is very useful for demonstration purposes for example with growers, advisors, administrators and policy makers. Generally, relatively simple models, with few and readily available inputs are used for practical DSSs while more complex models with more inputs tend to be used for scenarios analysis.

8.1 Simulation models for scenarios analysis of N management

Many of the simulation models developed to evaluate crop N management and its environmental impact are complex scientific models and their use has generally been restricted to scientific studies in which they are used as a means of aggregating knowledge or to conduct scenario analysis. Scenario analysis commonly takes two forms, being either: (a) demonstration of management consequences to stakeholders, or (b) as an alternative to costly experimental field trials with multiple treatments.

Generally, these models simulate N and water dynamics in the crop-soil system. Numerous such models have been developed, some examples are EPIC (Williams et al., 1984) one of the first such models developed and the basis for some subsequent models, STICS (Brisson et al., 2003), CropSyst (Stöckle et al., 2003), and the DSSAT group of models (Dayan et al., 1993; Jones et al., 2003). These are large and complex models which require numerous inputs, and which were generally developed for cereal crops. There have been a very small number of adaptations of these models to simulate aspects of N dynamics in vegetable crops (e.g. Cavero et al., 1998; Onofri et al., 2009; Rinaldi et al., 2007), but generally their use for practical N management of vegetable crops has been limited.

The comprehensive EU-Rotate_N model (Rahn et al., 2010) was developed as result of an EU funded research project to optimise N management in a wide range of vegetable and arable crops and rotations throughout Europe (Rahn et al., 2010). For many vegetable species, EU-Rotate_N simulates crop growth and marketable yield, crop N uptake and crop evapotranspiration. It considers N supplied by various sources such as soil mineral N, fertiliser N and N mineralised from soil organic matter, manures and crop residues, and water supplied by rain and various forms of irrigation. It can be used to conduct economic analyses and to assess negative environmental impacts through nitrate leaching and gaseous N losses. EU-Rotate_N has been used to simulate growth, production, and N and water dynamics in numerous diverse vegetable production systems such as various cool season species grown in open field conditions in Germany (Nendel, 2009), open field vegetable crops in Mediterranean conditions (Doltra and Muñoz, 2010) and in greenhouse-grown tomato and cucumber crops in SE Spain and China (Guo et al., 2010; Soto et al., 2014; Sun et al., 2012). The EU-Rotate_N model has been demonstrated to be an effective scenario analysis tool of N and irrigation management for different vegetable crops grown in diverse environments. By comparing scenarios, EU-Rotate_N can also be used to identify optimal N management. A feature of EU-Rotate_N is that the model considers crops grown in rotations, by considering rotation effects such as those of crop residues, residual soil mineral N throughout the profile, different rooting depths etc.

8.2 Decision Support Systems based on simulation models

Computer-based Decision Support Systems (DSS) can be used to calculate crop N fertiliser recommendations, and also crop irrigation requirements. The term “computer” here refers to all computing devices including smart phones and tablets. These DSSs can be stand-alone (i.e. installed directly on the device) or web-based programs (that can be consulted wherever there is an Internet connection). The use of computer technology enables numerous and frequent calculations to be made, various inputs to be considered, the use of stored data records for field and of data bases, and record keeping. Frequent calculation of N fertiliser requirements is essential for fertigated vegetable crops with frequent nutrient application. Relatively simple DSS with few data requirements are well-suited for on-farm use (Gallardo et al., 2014; Parneaudeau et al., 2009; Rahn et al., 1996).

Two broad modelling approaches are used for simulation models that are incorporated into DSSs. They are either “static” in that standard conditions are assumed such as expected yield and average climatic conditions, or they are “dynamic” in that they respond to real time or forecast conditions. Static approaches require less input data, data bases of long term average climatic data can also incorporated into the DSS so that there is no requirement to input climate data. Dynamic models simulate growth and production in the context of actual cropping conditions and have the capacity to respond to unseasonal weather and to weather fluctuations. Some DSS use both approaches, giving the user the option of either using a data base of average long term climatic data or entering real time climatic data as with the VegSyst-DSS (Gallardo et al., 2014). The use of long term average climatic data considerably simplifies the process of data entry, and is most suited to where there is small inter-annual climate variability such as in Mediterranean climates. With the rapid developments in Information and Communication Technology (ICT) it should be feasible to automatically enter forecast climate data (e.g. from 5–7 day forecasts). Where high frequency N application is employed (e.g. with fertigation/drip irrigation), this would enable N fertiliser planning for weekly period to be based on forecast climate conditions. It would also enable adjustment of provisional plans based on long term average climatic data.

Several DSSs based on simulation models have been developed in Europe to assist with N fertilisation of vegetable crops e.g. N-Expert (Feller, 2015; Fink and Scharpf, 1993), Azofert (Machet et al., 2007; Parneaudeau et al., 2009) and WELL_N (Rahn et al., 1996; 2001). The French DSS, Azofert was developed for cereals and vegetables, whereas WELL_N and N-Expert were developed primarily for N recommendations of vegetable crops, but also include cereals when grown in rotation with vegetables. The development of and the general procedures used by N-Expert were described in detail in section 3.3 of this chapter. N-Expert has been recently thoroughly revised and updated to produce N-Expert 4 (released in September 2015) for which information and free downloads in either English or German are available at: http://www.igzev.de/n-expert/?lang=en. The program is executable on all computer operating systems (as at September 2015). The N-Expert software assists growers and fertiliser advisers to calculate the N (and also P, K and Mg) fertiliser requirement of vegetable crops and also to prepare nutrient balances for N, P, K and Mg as required by the German Law. N-Expert 4 contains an updated database of nutrient uptake for all relevant field vegetable crops and for many other crops that are grown in crop rotations with vegetables. When compared with grower management in intensive vegetable rotations over five years, N-Expert reduced N leaching losses by 150 kg N ha^{-1} year^{-1} on average, with no significant effects on crop yield and quality (Armbruster et al. 2013).

The WELL_N DSS (Rahn et al., 1996; 2001) was developed as a practical DSS to determine N fertiliser recommendations in the United Kingdom. It has been used in commercial vegetable production by growers and advisors. WELL_N is based on routines of the previously developed research model N_ABLE (Greenwood, 2001). It considers average climate, soil mineral N, crop residues and N mineralisation from soil organic matter to calculate the minimum total amount of mineral N fertiliser required for maximum production of 25 different crops (Rahn et al., 2001). A default rate of N mineralisation from soil organic matter of 5 kg N ha^{-1} week^{-1} is assumed (Rahn et al., 1996).

The VegSyst-DSS, based on the VegSyst simulation model was developed to calculate daily irrigation and N fertiliser requirements and nutrient solution N concentrations [N] for fertigated vegetable crops grown in greenhouses in SE Spain (Gallardo et al., 2014). In this greenhouse-based vegetable production system, most crops are grown in soil, and all crops are grown with combined fertigation/drip irrigation, most receiving N in all irrigations (every 1–4 days), which is applied on the basis of concentration (Thompson et al., 2007b).

The VegSyst simulation model is a relatively simple model that calculates daily values of crop biomass production, crop N uptake and crop evapotranspiration (ETc). The model has been calibrated and validated for the major vegetable crops grown in greenhouses in SE Spain (e.g. tomato, sweet pepper, muskmelon, cucumber, zucchini, egg-plant, watermelon) (Gallardo et al., 2011; 2014; 2016; Gimenez et al., 2013). It is assumed that there are no water or N limitations on crop growth. The VegSyst-DSS calculates N fertiliser requirements, based on crop N uptake, by considering soil mineral N, and N mineralised from both the most recent manure application and from soil organic matter, and the efficiency with which N from each N source is used (Gallardo et al., 2014). Irrigation requirements are calculated based on ETc and by considering irrigation water salinity and the application uniformity (Gallardo et al., 2014). Irrigation is a determinant of the amount of applied N when N is applied on the basis of concentration. DSSs that calculate N requirements for fertigated vegetable crops, such as the VegSyst-DSS, must also calculate irrigation requirements.

The Veg-Syst DSS considers the planting date, length of cropping season, and climatic conditions of each crop; using either real time or long term average climate data, from an internal data base. Within greenhouse in the Mediterranean climate of SE Spain, there is little inter-annual climate variability, and long term average climate data show little deviation from real time data (Bonachela et al., 2006). When the database of long term average climatic data is used, the only required inputs for the Veg-Syst DSS are the species, the dates of the crop, some details of the soil and irrigation system, and information on the timing and amount of whitewashing used to limit excessive heat within the greenhouse. For the combined fertigation/drip irrigation systems used in SE

Spain, VegSyst DSS prepares daily plans of the recommended irrigation volume and of the recommended N concentration. For practical purposes, the recommended N concentration is also averaged over four weeks to reduce the number of adjustments to the composition of the fertigation solution. A stand-alone version of VegSyst DSS to operate with Windows operating systems is available at http://www.ual.es/GruposInv/nitrogeno/VegSyst-DSS.shtml.

Decision Support Systems for N management have been developed for leafy vegetables grown in open fields in California and Italy. In the Central Coast region of California (e.g. the Salinas Valley), the on-line DSS software CropManage (https://ucanr.edu/cropmanage/login/offline.cfm, click on “About CropManage”) has been developed to aid in the adoption of more efficient practices of N management to reduce NO_3^- leaching into underlying aquifers (Cahn et al., 2013). The CropManage software estimates N fertiliser and irrigation requirements on a field-by-field basis. The N fertiliser algorithm generates recommendations based on the crop N uptake, current soil NO_3^-–N status, and estimated soil N mineralisation. The irrigation scheduling algorithm uses real-time reference evapotranspiration data from Californian CIMIS climate station network (http://www.montecitowater.com/Cimis.htm), crop coefficients based on the planting configuration, and soil water holding characteristics to estimate irrigation intervals and volumes. Nitrogen management is based on adding sufficient N in periodic (e.g. weekly) applications to maintain root zone soil mineral N at a maximum threshold value of 15–20 mg NO_3^-–N kg^{-1}, based on the philosophy of the PSNT (described in Section 3.4 of this chapter). To improve the functionality of CropManage, an earlier version was thoroughly evaluated by growers in commercial lettuce fields and their feedback was incorporated into the software (Cahn et al., 2013).

A DSS that calculates N fertiliser recommendations for leafy vegetables has been recently developed in Italy (Massa et al., 2013). The simulation model within this DSS calculates the optimal amount of mineral N in the root zone to ensure maximum production whilst avoiding an excessive N supply. The N fertiliser recommendations are the amounts required to maintain the optimal soil mineral N content in the root zone. The underlying approach of maintaining an optimal root zone soil mineral N content is the same general approach for root zone N management described in Section 3.5 of this chapter. This DSS is based on the daily simulation of crop N uptake and a daily N balance calculation. The DSS was successfully tested in spinach (Massa et al., 2013).

FERTIRRIGERE (Battilani et al., 2003) is a DSS based on a dynamic model that assists in irrigation and nutrient management of processing tomato grown in Mediterranean regions. The main inputs are daily climate data (average temperature and wind speed, rainfall), and basic soil parameters (texture, nutrient content). Outputs are daily irrigation and macro nutrient requirements. When compared with grower management in 56 different farms in Tuscany (Italy), FERTIRRIGERE reduced N application by 46% on average, with no important effects on production and quality (A. Pardossi, University of Pisa, personal communication). FERTIRRIGERE (in Italian) can be freely downloaded (after registration) at http://cloud.consorziocer.it/CerAcqueNET/Login.aspx.

Researchers at the University of Pisa, Italy (Drs A. Pardossi, L. Incrocci and D. Massa) have developed a family of DSS for nutrient recommendations for vegetable crops in Tuscany, Italy. The CAL-FERT software (Incrocci et al., 2013) is a DSS that calculates fertilisation plans for N, P and K for various vegetable species by considering soil analysis, crop nutrient uptake and the mineralisation of nutrients from soil organic matter and decomposition of biomass of previous crops. It is available in Italian at http://www.cespevi.it/softunipi/calfert.html. The CAL-FERT software is an example of a static model that works with a target yield value, provided by the user, and a data base of long-term average climatic data. From the information of expected yield, cropping dates and climate conditions, CAL-FERT fits a crop N uptake curve which is then used with a daily N balance calculation to estimate daily N fertiliser requirements. Users can also input real time or forecast climate data.

The GREEN-FERT software is another DSS developed by the same researchers at the University of Pisa for managing fertilisation of various nutrients using the Dutch 1:2 volume soil:water extract method (Sonneveld and Voogt, 2009; Sonneveld et al., 1990) for different vegetable species grown in soil in greenhouses in Italy. The Dutch 1:2 volume soil:water extract method was described in Section 3.7 of this chapter. This software (in Italian) can be freely obtained at http://www.cespevi.it/softunipi/greenfert.html. GREEN-FERT contains a database for interpretation of the aqueous extracts; users can modify the database according to their personal experience. These researchers also developed the "Nutrient Solution calculator" which is an Excel™ spreadsheet developed to assist growers and consultants with the preparation of nutrient solutions for fertigation to usewr-specified recipes of nutrient concentration, EC and pH. This software is available in several different languages (EN, NL, ES, IT HU) at http://www.wageningenur.nl/en/Research-Results/Projects-and-programmes/Euphoros-1/Calculation-tools/Nutrient-Solution-Calculator.htm. Descriptions of the various nutrient management software programs developed by these researchers at the University of Pisa are available in Incrocci et al. (2013).

The NDICEA nitrogen planner (http://www.ndicea.nl/indexen.php) is a computer-based program developed by the Louis Bolk Instituut in The Netherlands that assists with N planning for vegetable and arable crops. It estimates N mineralisation from soil organic matter and different types of manures and organic residues, estimates N losses and performs weekly comparisons of crop N demand with net available N supply. This program has been in use for 15 years and is well known within the research community of organic agriculture. The model has been developed in The Netherlands. The latest version (from 2015) has The Netherlands, Flanders (Belgium), England, Denmark and Spain as pre-set country options, and has been used in several other countries. It offers a language choice of English, Dutch or Spanish. For use in other countries (with different soils, crops, manures, climate) the model can be adapted by changing the databases within the model and connecting it via Internet to obtain climate data from other weather stations.

The "Fertigation model" of Voogt et al. (2006) combines a crop evapotranspiration model with an empirical nutrient uptake model. It calculates on-going nutrient uptake concentrations (Thompson et al., 2013b) based on crop specific parameters such as cropping phase, plant height, LAI and real-time greenhouse climate data. Soil type, soil N-dynamics and the analytical results of regularly taken soil samples are used as parameters for adjustments (W. Voogt, Wageningen University and Research, The Netherlands, personal communication). The output is the composition of the nutrient solution which is used as input for a computer-controlled fertigation unit.

8.3 Decision Support Systems based on data bases

A DSS that is currently used in the United Kingdom is PLANET (Planning Land Applications of Nutrients for Efficiency and the environment; http://www.planet4farmers.co.uk/Content.aspx?name=PLANET) a nutrient management decision support tool developed for use by farmers and advisers in

England/Wales and Scotland. It has been developed for cereal and vegetable crops. PLANET incorporates computerised versions of both the RB209 Fertiliser Manual (described in Section 3.6 of this chapter) for England and Wales and Scotland's Rural College (SRUC) technical notes (http://www.sruc.ac.uk/downloads/120451/crop_technical_notes). It is essentially a database that contains and integrates all of the tables of the RB209 Fertiliser Manual and the relevant Scottish recommendations.

Additionally, it provides for detailed record keeping of individual fields and the capacity to update during cropping. Detailed records can be kept of cropping, soil analyses, and each fertiliser and manure application, and reports can be produced. PLANET also assesses compliance with the maximum N limit for individual crops and fields within Nitrate Vulnerable Zones (defined in Section 1 of this chapter).

9. Application methods

9.1 Split applications

Split N applications whereby the N is applied two or more times to a crop is a strongly recommended practice for vegetable production. Commonly, relatively small N applications are made immediately prior to planting and then one or more side-dress applications are made later during periods of rapid vegetative growth and fruit growth when the demand for N is much greater. Relatively small amounts of N are required for the period prior to the onset of rapid vegetative growth. Large single N applications at planting run the risk of appreciable N losses occurring, particularly when the amount of applied mineral N in the soil, mostly in the form of NO_3^-–N, appreciably exceeds the immediate crop N demand. The basic philosophy of split application is to partition N applications to coincide with crop demand. Most commonly, where split applications are made, one or two side-dress applications are made. The KNS system can be used to optimise side-dress N applications.

9.2. Fertigation

Fertigation is commonly used with drip irrigation, and is being increasingly used with sprinkler irrigation. In particular combined fertigation and drip irrigation systems are being increasingly used in vegetable production systems e.g. throughout southern Europe and in the central coast of California. With fertigation, N can be applied with varying degrees of frequency, depending on the irrigation schedule. Cahn et al. (2013) presented an example of five N applications by drip fertigation during a crop in California. In SE Spain, N applications to drip fertigated vegetable crops, grown in soil in greenhouses, are made every 1–4 days (e.g. Granados et al. 2013).

There are various types of fertigation systems in which nutrients are supplied to a crop through the irrigation system. These can be broadly categorised as being: (1) simple fertiliser tanks, (2) manually-operated multi-tank systems, and (3) computer-operated multi-tank systems. Generally, with category 1 systems, fertiliser is applied on the basis of rate, with category 2 systems as either rate or concentration, and with category 3 systems on the basis of concentration. With computer-operated multi-tank systems, nutrients are commonly applied in all or most irrigations; in combination with drip irrigation, there can be high frequency applications of both water and nutrients.

The combined use of fertigation and drip irrigation provides the technical capacity to spoon-feed N and irrigation as required by the crop. Applying frequent small N applications can appreciably reduce the risk of N loss associated with larger, more infrequent N applications as occurs with split applications. However, the growers generally lack the tools to take advantage of this advanced technical capacity for precise N management. To do so, both irrigation and N management have to be optimised. Excessive irrigation with an optimal concentration of N will result in the application of excessive N. Similarly, excessive N application without optimal irrigation can result in a large accumulation of soil mineral N that can be subsequently lost to the environment (Soto et al., 2015). The recommended approach for optimising both irrigation and N management of fertigated vegetable crops is a combination of prescriptive and corrective management for both irrigation and N (Granados et al., 2013). Prescriptive management is the preparation of detailed plans of recommendations for both irrigation and N fertiliser applications, which can be prepared using DSSs (see Section 8.2 of this chapter). Corrective management is the use of monitoring techniques to identify adjustments that ensure that the supply of water and N maintains the desired crop water and N status. Monitoring approaches for N management were discussed in Sections 3.7, 3.8, 5.4 and 6 of this chapter. Monitoring methods for irrigation of vegetable crops were reviewed by Gallardo et al. (2013).

10. Specialised fertilisers

10.1 Fertilisers with nitrification inhibitors

Nitrification inhibitors (NI) appreciably slow the otherwise rapid process of nitrification *i.e.* the transformation of ammonium (NH_4^+) to NO_3^-, in soil, during a period of time. By slowing and delaying nitrification, NIs reduce the possibility of N losses of root zone NO_3^- by NO_3^- leaching and denitrification, and also reduce nitrous oxide (N_2O) emissions associated with both nitrification and denitrification. The most commonly used chemical nitrification inhibitors are 3,4-dimethylpyrazole phosphate

(DMPP) and dicyandiamide (DCD) (Gilsanz et al., 2016; Pasda et al., 2001; Zerulla et al., 2001). Nitrification inhibitors are combined with NH_4^+ based fertilisers; commercial products are available, such as the widely distributed ENTEC® range which incorporates DMPP. ENTEC® fertilisers are distributed by the company EuroChemAgro (http://eurochemagro.com/products/entec/). There has been considerable interest in recent years in their use to reduce nitrous oxide (N_2O) emissions associated with nitrification and denitrification (e.g. Gilsanz et al., 2016; Zhang et al., 2015). A number of studies have demonstrated their capacity to appreciably reduce N_2O emissions from intensive vegetable production (e.g. Scheer et al., 2014; Cui et al., 2011; Pfab et al., 2012; Zhang et al., 2015).

For practical N management, NIs provide the possibility of a reduced number of N fertiliser applications in vegetable production. This can be particularly advantageous for conventional surface applications of N fertiliser, and for short season crops such as lettuce where their use may ensure that a single pre-planting N application provides sufficient N for the entire crop. Their use can reduce the number of N fertiliser applications and maintain yields of vegetable crops (Pasda et al., 2001). Other benefits that have been reported with vegetable production include less NO_3^- accumulation in leafy vegetables (Irigoyen et al., 2006; Pasda et al., 2001) and reduced NO_3^- leaching loss (Cui et al., 2011). From a commercial farming perspective, the benefits to be gained from the use of NIs must be balanced against the additional cost of NH_4^+ based fertilisers containing NIs.

The overall effect of nitrification inhibitors is to delay nitrification. Therefore, if excessive N fertiliser is applied and the period in which the applied stabilised NH_4^+ does not coincide with crop N uptake, the delayed formation of NO_3^- may simply result in delayed N losses to the environment. Additionally, to be effective, their rate of degradation and their possible movement in soil should be taken into consideration within the given cropping conditions.

An important consideration is the possible uptake of NIs, and their degradation products, by vegetable crops. Nitrification inhibitors are subject to extensive standard toxicology and ecotoxicology testing prior to commercial release (Zerulla et al., 2001). Nevertheless, consumers and retailers will be concerned about the presence of these compounds and/or their degradation products in vegetable products. Plant absorption of DCD by wheat and subsequent metabolism within the plant was reported by Marsden et al. (2015). Where NIs are used in vegetable production, the routine analysis of edible products for the NIs and their metabolites, as occurs with pesticides, should be considered where it is not mandatory. Where NIs are present in edible vegetable products, there are established acceptable daily intake limits for the active compounds that are part of the toxicological evaluation in the registration process (Pasda et al., 2001).

Nitrification inhibitors may have a role to play in vegetable production for reducing the number of N fertiliser applications and/or reducing N_2O emissions. However, given the concern of consumers and sales outlets regarding the presence of agrochemical and their derivatives in food, appreciable attention will need to be paid to ensure that there are no or at least minimal concentrations of NIs and their derivative compounds in edible vegetable products. Research will be required to better understand the uptake of NIs and metabolites by different vegetable species, and of the processes of the metabolism of NIs within vegetable plants. Where NIs are used in commercial farming, testing for NIs and their principal metabolites may need to be incorporated into the routine analysis of agrochemicals that is commonly associated with vegetable products.

10.2 Slow and controlled release fertilisers

The terms “slow release fertilisers” and “controlled release fertilisers” have been used interchangeably and also separately. Slow release fertilisers (SRF) have been defined as those from which nutrient release is slower than from the commonly-used mineral fertilisers, and where the rate, pattern and duration of release are not well controlled (Shaviv, 2001). Controlled release fertilisers (CRF) have been defined as those where the factors dominating the rate, pattern and duration of release are well-known and controllable during the preparation of the CRF (Shaviv, 2001). Here these fertilisers will be considered collectively as “slow and controlled release fertilisers” (SCRF).

Slow and controlled release fertilisers are a very active and constantly evolving area of research. The current discussion will focus on the most important and established nitrogen SCRFs. Organic and processed organic fertilisers will not be considered, nor will fertilisers with urease inhibitors. The focus here will be on mineral nitrogen SCRF fertilisers. There are two broad categories of mineral nitrogen SCRF fertilisers.

The first broad category is of products in which the N source, generally urea, has been chemically reacted with a compound to slow the release of N; microbial and chemical decomposition processes slowly release the N into the soil solution (Guertal, 2009; Shaviv, 2001). There are two main sub-groups within this category: urea-formaldehyde products (UF) and isobutylidene diurea (IBDU). Urea-formaldehyde is formed by reacting urea with formaldehyde at varying temperatures and reaction times, both processes influence the length of chains produced of combined urea and carbonhydrogen groups. The length of the chains negatively influences the rate and positively influences the duration of N release (Guertal, 2009).

The second sub-group within this broad chemically-stabilised of urea products is IBDU which is a combination of urea and isobutyraldehyde (Guertal, 2009). Nitrogen is released following hydrolysis of IBDU, N release is faster with smaller particle size and faster with warmer soil temperatures (Guertal, 2009). This first broad category of SCRF is regarded as being slow release fertilisers (Shaviv, 2001) because there is less control over the rate of N release than with other forms of SCRF.

The second broad category of SCRF is that of fertilisers that have a physical coating around a physical unit of mineral N fertiliser, which is most commonly a urea prill. Typical coating materials are sulphur, wax, resin, polymer or a combination of these materials (Guertal, 2009). Sulphur coated urea has been used since the 1960s (Shaviv, 2001), and more recently, resin or polymer coatings have been used (Guertal, 2009; Shaviv, 2001). Nitrogen release from coated products is influenced by coating thickness, orifice size in the coating, soil moisture, soil temperature, and soil microbial activity (Guertal, 2009). An example of a resin coated SCRF is the commonly-used Osmocote® domestic fertiliser. Coated SCRFs are regarded as controlled release fertilisers because variations in coating material, coating thickness orifice size provide some control over the N release rate (Guertal, 2009; Shaviv, 2001). A comprehensive review of coating materials is provided by in Shaviv (2001).

Slow and controlled release N fertilisers potentially enable a single N fertiliser application to provide the complete N requirement of a vegetable crop with an appreciably reduced risk of N losses. They are more expensive than conventional mineral N fertiliser per unit of N. Agronomic studies with vegetable crops have generally reported similar yields from single applications of nitrogen SCRF compared to conventional N management (Guertal, 2009). One possible disadvantage in the context of vegetable production is ensuring sufficient crop available N when there is a rapid increase in crop N demand during the exponential growth phase (Guertal, 2009).

Despite the considerable research activity with SCRF, they have a very small market share. Shaviv (2001) reported that they comprised about 0.15% of all fertiliser sales, but that their use had doubled in the preceding ten year period. The vast majority of SCRF were sold for non-agricultural markets (e.g., turf, golf courses, landscaping) (Shaviv, 2001). Agriculture accounted for slightly more than 10% of total SCRF use, but the demand was increasing at an annual rate of about 10% (Shaviv, 2001). In the USA, only a small proportion of total agricultural use occurs with vegetable crops (Morgan et al., 2009). In general, it seems that to date, there has been little use of SCRF in vegetable production.

Slow and controlled release fertilisers are well suited to situations where crops are present for prolonged periods (e.g. turf, golf courses, fruit trees), where their use confers an economic advantage by reducing fertiliser application. In the case of vegetable production, where crops are commonly of short duration, vegetable growers may not perceive sufficient economic advantage, through reduced N applications, to justify the extra cost of SCRF (Morgan et al., 2009). An additional and important issue with vegetable cropping is to ensure the N supply during periods of peak N demand; SCRF may not always be able to provide sufficient amounts of readily available N.

In general, research with SCRF in vegetable crops has shown similar but not higher production than with conventional N management (Guertal, 2009), and until now the economics of reduced N fertiliser application have not convinced many vegetable growers. It is possible that for environmental reasons that legislation may encourage adoption of SCRF. If there is to be appreciably increased use of SCRF in vegetable production for environmental reasons, it should be based on sound scientific research demonstrating reduced N losses under diverse realistic cropping conditions. It is likely that the potential use of SCRF in vegetable production may be influenced by the characteristics of cropping systems. Hartz and Smith (2009) commented that the use of SCRF for environmental reasons may be most suitable where appreciable in-season NO_3^- leaching loss is likely and where this was beyond the control of the grower. These authors considered that this was not the case in the Mediterranean climate of California, which would also apply to vegetable crop grown in other regions with Mediterranean climates and also to greenhouse-grown crops. Examples of more suitable regions for the use of SCRF are areas with heavy rainfall events during cropping and on sandy soils.

11. Future developments

The coming years will see an increasing availability of low-cost sensors that will potentially enable rapid in-field monitoring of crop and soil nutrient status, enabling in-season adjustment of fertilisation plans according to crop specific conditions. Additionally, tools (Apps, DSSs) will be developed for mobile computer devices (smart phones, tablets) that will provide the means to prepare crop specific fertiliser plans and to very rapidly interpret data from sensors.

These technologies individually provide appreciable potential to improve nutrient management. Together, the combination of planning and monitoring tools provides considerable potential for optimal nutrient management, particularly for N (e.g. Granados et al., 2013), as was outlined in section 9.2 of this chapter. Following the preparation of a crop specific nutrient management plan that considers the site and season specific requirements of a given crop, monitoring tools can then be used to ensure that optimal nutrient status is maintained. The challenge facing researchers, developers, and Extension staff is to develop user-friendly and effective applications of these technologies, to demonstrate their practical value to vegetable growers, and to effectively support growers in using them.

It seems very likely that in the coming years, in many different regions, there will be strong political and social pressure on vegetable growers to adopt management practices that reduce N losses to the environment. Therefore, it also seems likely that there will be increasing adoption of the strategies and tools outlined in this chapter.

12. General considerations

Optimal N management of vegetable crops is something that cannot be done in isolation; it must be part of a complete crop management package in which all aspects of crop management are optimised e.g. irrigation, other nutrients, pest, disease and weed management. Otherwise the effect of the improved N management practices may be limited.

The choice of which procedures to use will be influenced by numerous factors. A major determinant is what is on offer; that is which recommendation schemes or tools are available through local Extension services or other service providers. These schemes and tools should all be adapted to local cropping and general farming conditions. For a given region, the schemes and tools provided should be appropriate to the technological level of local growers, the nature of the crop (e.g. length of growing season, crop morphology), the number and frequency of N applications, economic considerations and very importantly, the level of available support. These same considerations are relevant for individual growers when selecting an approach or tool to use.

13. Conclusions

There is range of tools and strategies that can assist vegetable growers to improve N management. These include various methods based on soil analysis or estimation of the soil N supply, N balance calculations, methods based on plant analysis, methods based on monitoring crops with optical sensors, and the use of computerised decision support systems based on simulation models or data bases. Use of these tools has been demonstrated to appreciably reduce fertiliser N application and N losses while maintaining production. Basic strategies for improving N fertiliser management are to consider all N sources such as root zone soil mineral N and N mineralised from organic materials, and to partition N application so that N applications coincide with crop N demand.

Developments in planning approaches can provide site and crop specific nutrient plans for individual crops. On-going developments in monitoring approaches should, in the near to intermediate future, provide tools that ensure optimal crop N status. Combinations of planning and monitoring approaches, particularly when combined with both fertigation and drip irrigation, provide the potential for precise optimal N management of vegetable crops.

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