Strategies for optimal fertiliser management of vegetable crops in Europe

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Abstract

In Europe a number of procedures are used to assist growers and advisors to determine optimal N fertiliser recommendations. The implementation of European Union (EU) legislation is encouraging the adoption of fertiliser recommendation schemes. The most widely used schemes are those based on soil testing or on the use of indices that estimate the soil nitrogen supply. Soil testing approaches that are in use, particularly in NW Europe are the Nmin, KNS and N-Expert systems; the latter is operated as a computer-based decision support system (DSS). The comprehensive RB209 Fertiliser Manual of England and Wales uses soil N supply indices, but soil analysis can also be used. Nitrogen balance calculations are widely used throughout Europe and form part of the KNS and N-Expert systems, and a number of other DSSs. The N balance considers the various soil N sources and treats mineral N fertiliser as a supplemental N source. The EU-Rotate_N simulation model is a comprehensive and versatile tool, developed for diverse European conditions, that is useful for scenario analysis simulations to stakeholders. Various DSS have been developed in different European countries, with different levels of complexity. There are a number of different DSS that calculate N fertiliser recommendations for particular cropping systems; some DSS calculate the requirements for other nutrients, and some also do so for irrigation which is particularly useful where fertigation is used. Sap analysis has been shown to be sensitive to crop nutrient status, for N and some other nutrients; currently, there is renewed interest in sap analysis. Proximal optical sensors are a promising approach for N management.

Keywords: soil analysis, decision support systems, crop monitoring, simulation models

INTRODUCTION

This article will focus on the management of N fertilisation because of its economic importance and because of the environmental problems associated with losses of N fertiliser to the environment, in particular NO_3^- contamination of groundwater and the eutrophication of surface waters. N fertiliser is generally essential to maintain high yields and profitable production.

Commonly, vegetable growers supply N that is excessive to crop requirements (Thompson et al., 2007). This often results in appreciable N losses to the environment and consequent environmental problems. In addition to mineral N fertiliser, the N supply includes N mineralised from organic amendments and from soil organic N and mineral N present in the root zone at planting. Good N management requires that these various sources of N be considered and that mineral N fertiliser be regarded as supplementary N to ensure that crop N requirements are met without a large excess of N being supplied to a crop.

In the European Union (EU), increasing pressure is being applied to reduce the environmental problems associated with N fertiliser use. Two pieces of EU legislation, the Nitrate Directive (Anon., 1991) and the Water Framework Directive (Anon., 2000) are forcing the imposition of improved management of N fertiliser. These pieces of legislation

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require all farmers in areas affected by environmental problems caused by N fertiliser use to adopt improved N management practices. Currently, these pieces of legislation have been most strongly implemented in the Netherlands, Belgium, Denmark and Germany; it is considered to be a matter of time before there is strong implementation in the rest of the European Union.

Various strategies have been or are being developed to enhance N management in Europe; generally, they consider crop N requirements and either explicitly or implicitly consider the sources of N other than mineral fertiliser N. Historically, the north-western (NW) European countries have been the most advanced regarding the development and implementation of these strategies.

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SYSTEMS BASED ON SOIL ANALYSIS OF ROOT ZONE MINERAL N

The Nmin, KNS and N-Expert family of systems

The Nmin, KNS and N-Expert family of systems of N recommendation are used in NW and Central Europe. The three methods calculate "N target values" for a given species which is the crop N requirement which is met by the sum of fertiliser N and soil mineral N. N target values represent the total supply of mineral N required to ensure that the crop does experience a N limitation. The N fertiliser recommendation is calculated as the target value minus the soil mineral N measured in the soil. With the KNS and N-Expert systems, N mineralised from organic materials (soil, manure, crop residues) is usually also subtracted from the N target value. The Nmin, KNS and N-Expert were developed in sequence and represent an on-going development.

1. The Nmin system.

"Nmin" refers to mineral N, and not to N mineralised from organic material. This system has been used to assist with N fertiliser recommendations of field-grown vegetable crops in NW and Central Europe since the early 1990s. It is currently used in Denmark and parts of the Netherlands for open field vegetable crops.

The system was originally described by Scharpf (1991). In this system, the recommended amount of mineral N fertiliser for the entire crop is the N target value minus the amount of soil mineral N in the root zone at planting. 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:

$$\text{N fertiliser recommendation} = \text{N target value - root zone soil mineral N} \quad (1)$$

Soil mineral N in the root zone (Nmin) is the sum of NO_3^--N and NH_4^+-N. However, generally only NO_3^--N is measured because usually NH_4^+-N is rapidly nitrified. Additional measurement of NH_4^+-N is recommended after recent application of organic fertilisers or mineral NH_4^+ fertilisers when appreciable amounts of NH_4^+-N are expected. N mineralisation is not explicitly considered, as it is implicitly considered in the experimental determination of the N target value.

The N target values of the Nmin system are experimentally-determined in fertiliser trials conducted at representative field sites. This is an expensive and time consuming requirement. It may be feasible to do so for major crops in important vegetable cropping areas where there are well-funded extension programs. However, to develop N target values for all commercially-grown vegetable species within a region considering different species, locations and soil types would require a very large number of fertiliser trials even where there are well-funded extension services. Some regions simply do not have the Extension services to carry out even a limited number of fertiliser trials. Given the requirement for numerous fertiliser trials, it is not surprising that the Nmin system has been mostly used in the wealthier countries of NW and Central Europe.

The requirement for fertiliser trials is a major limitation for the use of this system. Additional limitations are that N target values are for fixed yields, and that the Nmin system provides a single N fertiliser recommendation for a crop; it does not provide information on the partitioning of the fertiliser application.

2. The KNS system.

The KNS system developed by Lorenz et al. (1989) is a modification of the Nmin method in which a N balance calculation is used, and the root zone mineral N is sampled two or more times. This N recommendation system is used in parts of north-western (NW) and Central Europe, and is the most commonly used system in Flanders, Belgium. The target N value is calculated as the expected crop N uptake plus a buffer value of root zone soil mineral N. The buffer value is a species-specific quantity below which the immediate soil N supply limits crop production. The N fertiliser rate, which is often determined two or times in a crop, is the target N value minus the measured amount of root zone mineral N at the beginning of the period being considered.

The KNS system does not require comprehensive fertiliser trials to experimentally determine N target values and does not assume fixed yields. The crop N uptake values are provided to users in tables or graphs. N crop values are derived from various sources such as 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 to implement the Nmin system.

To consider variations on the average yields used by the KNS system, manual adjustments are made to increase or lower crop N uptake values. The KNS system aims to enhance the accuracy of N fertiliser recommendations by applying part of the total N requirement at planting and to adjust the subsequent N top dressing according to a very recent soil mineral N analysis.

The 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, and are appreciably lower when there is a concern of nitrate accumulation in susceptible leafy crops. In Germany, for many vegetable crops, the N buffer value is 40 kg N ha^{-1}, the highest value of 80 kg N ha^{-1} is for broccoli and cauliflower, and the lowest value of zero is used for carrots intended for baby food.

The procedure used in the KNS system is described subsequently. Target N values are calculated according to Equation 2:

$$\text{N target value} = \text{N crop} + \text{N buffer} \tag{2}$$

where N crop is crop N uptake during the specified period, N buffer is the buffer value of required soil mineral N in the root zone at the end of the specified period. 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 full calculation for the N fertiliser recommendation in the KNS system follows Equation 3.

$$\text{N fertiliser recommendation} = \text{N target value} - (\text{N mineralised from soil organic matter} + \text{soil mineral N in the root zone}) \tag{3}$$

Lorenz et al. (1989) suggested a fixed value of 5.5 kg N $week^{-1}$ for N mineralisation from soil organic matter for the Rhineland Palatinate region in Germany. In practice, the N mineralisation term is sometimes overlooked, which will reduce the accuracy of the estimation of the N fertiliser recommendation.

A detailed example of the use of the KNS system to calculate N target values and N fertiliser recommendations is provided by Ziegler et al. (1996). In the example of Ziegler et al. (1996), N mineralisation was not included in the calculation of the N fertiliser requirement.

3. The N-Expert system.

The N-Expert decision support system (DSS) is a computer program that is a further development of the KNS system; it was first described by Fink and Scharpf (1993). N target values calculated by the N-Expert system are the legal basis for calculating N fertiliser recommendations compliant with the German Fertiliser Ordinance. The further development in relation to the KNS system is that N losses are considered together with N mineralisation in the component "apparent N mineralisation". The "apparent N mineralisation" component also considers that crops recover 80% of the N supply. The "apparent N mineralisation" component is included in the calculation of the N target value, as in Equation 4:

$$\text{N target value} = \text{N crop} + \text{N buffer} - \text{apparent net N mineralization} \qquad (4)$$

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

For transplanted crops, soil sampling and fertiliser application are generally conducted shortly before planting. For sown crops with slow early development, soil sampling and fertiliser application are generally conducted 4-6 weeks after sowing.

The recently revised (September 2015) N-Expert 4 software can be downloaded at http://www.igzev.de/n-expert/?lang=en. A comprehensive, up to date table of N-Expert's N target values for commercially relevant field vegetables in northern Europe is available as a free download (Feller et al., 2015).

Soil testing based fertiliser recommendations in the Netherlands

1. Restrictions on N fertiliser use.

Generally the N-fertilisation of field vegetables in the Netherlands is based on an official fertiliser recommendation system. For all fields, the total annual N supply in the form of manure and mineral fertiliser N has a maximum limit (RVO, 2015a), in accordance with the EU goals to limit NO_3^- in ground and surface waters. Maximum annual N limits are established for each crop with differentiations for soil type (RVO, 2015b).

2. Recommendation procedures.

To support growers and farmers, recommendation systems have been adapted to comply with these regulations (De Haan and van Geel, 2013). Before the growing season starts, a balance sheet calculation (see Section on The N Balance Calculation) must be made according to the cropping plan, soil type, and crop type. Fields have to be sampled at three soil depth layers (0-30, 30-60, 60-100 cm) and analysed for mineral N, and other nutrients (CBAV, 2015). At least one composite sample is taken per two ha. Samples are analysed for mineral N following extraction with 0.01 M $CaCl_2$ (Houba et al., 1990).

The recommended total N fertiliser requirement for each field is calculated according to the cropping plan and soil type, using crop-specific tables that relate N recommendations to Nmin (NH_4^+-N plus NO_3^--N) in 0-60 cm soil. These relationships have been established for all vegetable crops, and for some species, for individual growing season where that is appropriate (CBAV, 2015). When determining the N recommendation, other factors are taken into account such as estimated N mineralisation from soil organic matter and from residues of the preceding crop, the expected moisture conditions and irrigation. Additional considerations are the cultivar to be grown and the grower's experience with the individual field.

3. Pre-plant N application.

The total recommended N application is split into parts for the pre-plant application and the top dressing application. Pre-plant applications are based on ensuring that there is the required buffer amount of Nmin in the soil; the buffer amounts differ between crops, varying from 50 kg N ha^{-1} for lettuce to 90 kg N ha^{-1} for winter leek. The quantity applied is obtained from balance sheet calculation for Nmin in 0-30 cm soil. Corrections on the calculated N application are made for N supplied by green manures and crop residues. In the case of green manures ploughed under in early spring, the N requirement is reduced by between 60 kg N ha^{-1} for legumes and 40 kg N ha^{-1} for *Cruciferae*. For crop residues, the size of the reduction in the N fertiliser requirement depends on the previous crop and varies from 20 kg N ha^{-1} for crops like leek, fennel and beetroot, to 60 kg N ha^{-1} for brussel sprouts. Depending on the fertiliser application method, the N fertiliser recommendation may be adjusted. For example, with band application of mineral N fertiliser, the recommended quantity of N fertiliser may be reduced by as much as 40 kg N ha^{-1} (Everaarts, 2000).

4. N side dressing.

For N side dressing of field vegetables crops in The Netherlands, the NBS system is used. The system is based on the previously-described KNS system (Lorenz et al., 1989); in using this system, crop growth conditions are anticipated. The factors considered by the NBS system are the crop N uptake curve throughout the crop, the buffer value of soil mineral N, and N mineralisation during the crop. Soil analyses are conducted one or two times during the crop cycle, in addition to the sampling that was previously made to determine the pre-planting N application.

The N fertiliser recommendation at a given time is calculated using Equation 5:

$$N_{supply}t_1 = (N_{crop}t_2 - N_{crop}t_2) - N_{min}t_1 + N_{Buf} - N_{org} \quad (5)$$

where: t_1 = time of assessment; t_2 = scheduled time of the next assessment; $N_{supply}t_1$ = N fertiliser application at time t_1; $N_{crop}t_n$ = estimated amount of N taken up by the crop at times t_1 and t_2; $N_{min}t_1$ = soil mineral N at time t_1; N_{Buf} = required buffer of mineral N in soil profile to 60 cm; N_{org} = expected N mineralisation between time t_1 and t_2.

The scheduling of top dressing assessments (t_n) and the amounts of the individual mineral N fertiliser application ($N_{min}t_n$) are established for each crop. Depending on weather conditions these may vary between individual crops of the same species. The buffer value of soil mineral N is based on empirical data and experience.

The estimation of N mineralisation usually uses a default value; commonly, this is not explicitly considered as it is assumed to be included within the buffer value of soil mineral N. In the case of crop residues, green manures and organic soil amendments, N mineralisation is calculated and explicitly considered. Currently, for practical advisory work, simple rules of thumb are used to determine when additional N mineralisation is explicitly considered for a given period.

There are NBS guidelines for a number of vegetable species and for potato. The NBS system is flexible and can be calculated at any time. There is flexibility throughout the period during which the crop is fertilised, for example adjustments can be made when there is unexpected heavy rainfall. It is important that the amount of soil mineral N is reliably determined. Side dressings must be carried out with very soluble, rapidly-acting mineral N fertilisers. Where slow-release fertilisers are used for pre-planting applications, the release of N over the period of interest must be estimated.

In the last decade there has been increased use of liquid fertilisers including many by-products from processes in the agro-industry such as digestate from biogas production, and products from manure treatments and air-washers (NH_4SO_4). Basically the effect of liquid fertilisers on yield and crop performance are not different from crystalline fertilisers, the major advantage is in the possibility of improved fertiliser placement by which the N use efficiency (NUE) can be increased (Schröder et al., 2015).

The RB209 System of England and Wales

The "RB209 Fertiliser Manual" (AHDB, 2010) uses indices to estimate the soil N supply (SNS) for a given field and then these SNS indices are used to determine the N fertiliser recommendation for a given vegetable or crop species. SNS Index values are estimates of the crop available N (soil mineral N plus N mineralised from crop residues). The SNS indices have values of 0-6, and each index value corresponds to a different incremental supply of soil mineral N in the root zone (in kg N ha^{-1}). For SNS indices of 0-6, the respective amounts of N supplied are ≤60, 61-80, 81-100, 101-120, 121-160, 161-240 and >240 kg N ha^{-1}.

For a specific field, the appropriate SNS index is determined by using tables which consideraverage annual rainfall, soil texture and residues from the proceeding. Once the soil N supply has been estimated for given field, the recommended fertiliser N rate for that SNS Index is determined. Separate tables relate the recommended N fertiliser rate to SNS Index values for each species. There are tables for many vegetable and arable species. Using lettuce as an example, SNS Index values of 0 to 6, correspond to recommended N fertiliser rates of 200, 180, 160, 150, 125, 75, and 30 kg N ha^{-1}.

Rahn (2012) described the use of the RB209 Fertiliser Manual to determine N fertiliser recommendations. Measurements of soil mineral N, at planting, can be incorporated into the recommendation procedure (Rahn, 2012) and are suggested for certain situations such when there are high or uncertain amounts of crop residue (Rahn, 2012). The complete RB209 Fertiliser Manual can be freely downloaded at AHDB (2010). The RB209 Fertiliser Manual is a comprehensive guide to fertiliser management; it covers many crops, deals with different zones, soil types and management practices, and contains detailed explanations and considerable useful supplementary information. A revision of the RB209 Fertiliser Manual, the AHDB (Agriculture and Horticulture Development Board) Nutrient Management Guide is scheduled for release in 2017.

The freely-available PLANET software program (DEFRA, 2014) is a computerised form of the RB209 Fertiliser Manual; it uses a series of data bases to estimate the required SNS Index values and N fertiliser recommendations. It also enables record-keeping and evaluates if N management complies with the requirements of EU Nitrate Directive (see Introduction) in affected areas where compliance is required. Many growers in England and Wales have a copy of RB209 or PLANET (C. Rahn, pers. commun.). While it is difficult to know how many growers actually regularly use these recommendations, it seems many growers do.

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. 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.

THE N BALANCE CALCULATION

The N balance calculation is used in various European N fertiliser recommendation schemes such as the KNS, N-Expert and NBS systems, described previously, and in various European decision support systems, such as N-Expert, VegSyst-DSS and Azofert which are described subsequently. It is a commonly recommended procedure in numerous European countries where recommendation schemes such as those referred to above have not been implemented. The N balance calculation determines the amount(s) of mineral N fertiliser to be applied for an entire crop or for periods within a crop. The determination of N fertiliser application amount using N balance calculations has the advantage of explicitly considering all major N inputs of crop available N. In its simplest form, N balances are calculated for the duration of a crop.

With the use of decision support systems that incorporate simulation models such as VegSyst-DSS, N balances can be calculated daily or weekly enabling site, crop and season specific N management. When used with daily or weekly time steps, N balance calculations can be used with frequent N application through fertigation/drip irrigation systems.

Generally, the amount of soil mineral N in the root zone, at the beginning of the period of interest, is a required input. Additional soil analyses, or plant analyses, can be used as feed-back to adjust parameters. The most commonly-used N inputs and outputs are listed in Table 1. The term "N mineralised from organic residues" includes crop residues and soil amendments such as manure applications. Additional N inputs such as N applied in irrigation water are used where appropriate.

Table 1. N inputs and outputs used for developing a N balance.

N inputs	**N outputs**
Initial soil mineral N ($N_{min\text{-}ini}$)	Crop N uptake (N_{crop})
N mineralised from soil OM ($N_{mins\text{-}OM}$)	N losses (N_{loss})
N mineralised from org. residues ($N_{mins\text{-}res}$)	Final soil mineral N ($N_{min\text{-}fin}$)
Mineral N fertiliser (N_{fert})	
Total N inputs (∑Inputs)	**Total N outputs (∑Outputs)**

For each given time period, the sum of N inputs equals the sum of N outputs. The N balance is used to calculate amount of N to apply as mineral fertiliser, using the general approach of equation 6:

$$N_{fert} = N_{outputs} - N_{inputs} \text{ (apart from } N_{fert}) \tag{6}$$

where N_{inputs} are all N inputs with the expecption of mineral N fertiliser (N_{fert}).

There are various approaches for calculating the N_{fert} term (Tremblay et al., 2001; Meisinger et al., 2008; Gianquinto et al., 2013). Consistent to all approaches is that all major N sources are considered. One practical approach is the use of a quantity of buffer soil mineral N at the end of the calculation period (Tremblay et al., 2001; Gianquinto et al., 2013), as in the KNS method. The use of the buffer quantity of soil mineral N ensures that soil mineral N does not limit production, and avoids the difficulty of estimating the apparent recovery or efficiency value (E) for N use by a crop (Gianquinto et al., 2013) as in the alternative approach described below.

Tremblay et al. (2001) used the following equation (Equation 7):

$$N_{fert} = (N_{crop} + N_{Buffer\ min} + N_{Immobilis.}) - (N_{min\text{-}ini} + N_{mins\text{-}OM} + N_{mins\text{-}res}) \tag{7}$$

Where $N_{Buffer\ min}$ is the buffer amount of soil mineral N and $N_{Immobilis}$ is an estimate of N immobilisation calculated as (N_{crop} + $N_{Buffer\ min}$) × 0.15. The other terms are explained in Table 1.

Another approach is to calculate N fertiliser requirements by estimating the apparent recovery or efficiency of use (E) of each N input as N_{crop}/N-Input (Meisinger et al., 2008); it is simplistically assumed here that the efficiencies of use of all inputs are the same. All N losses through leaching, denitrification and immobilisation are implicitly considered as being the N not recovered by the crop. Crop fertiliser requirements can be calculated using the equation:

$$N_{fert} = (1/E) * [N_{crop} - (N_{min\text{-}ini} + N_{min\text{-}OM} + N_{mins\text{-}res})] \tag{8}$$

These terms are all explained in Table 1.

N balance calculations form part of a number of numerous European N fertiliser recommendation schemes and decision support system. These calculations represent two fundamental aspect of good crop N management in that 1) all sources are considered, and 2) mineral N fertiliser is used to supplement the crop available N supplied by the other N sources.

PLANT TESTING APPROACHES

Plant tissue analysis, mostly in the form of analysis of leaf samples (generally the most recently fully expanded leaf) has been, for several decades, an established method to assess crop nutrient status for a wide range of nutrients (Geraldson and Tyler, 1990; Hartz and Hochmuth, 1996). Generally, tissue analysis has been used mostly for diagnosis when visual signs of nutritional problems are apparent.

In the 1980s, sap analysis was introduced as a more rapid procedure for assisting in fertilisation management. Mansson (1984) introduced a laboratory method with rapid analysis of leaf sap to assist with nutrient management of fertigated crops; not only for N (based on NO_3^- analysis) but also other macro nutrients and for micro nutrients. Around that time, a method for plant sap testing to assist with N management was introduced for potatoes, in which the petiole sap NO_3^- concentration was determined (Westcott et al., 1993). Olsen and Lyons (1994) reported that for determining N status of sweet pepper that petiole sap NO_3^- concentration was much more sensitive than leaf total N content. A major advantage of sap analysis compared to tissue analysis is that growers can quickly perform the analysis of sap NO_3^- concentration in the field using hand-held meters (Thompson et al., 2009; Parks et al., 2012). However, on-farm analysis should be done with considerable care (Parks et al., 2012) and with regular verification; generally, analysis carried out by trained technicians in an efficient, local, laboratory, is preferable (Parks et al., 2012).

Petiole-sap testing has been used to a certain extent to assist with decisions about side dressing crops such as potato, tomato and other vegetables(Farneselli et al., 2010; van Geel et al., 2014). Other authors concluded that plant sap testing could be a useful supplementary tool, but that it required further development (Matthäus and Gysi, 2001). Sonneveld and De Bes (1983) showed that plant sap reflected very well crop nutrient status for N and K and did so quite well for Mg, P, and only to a limited extent for other nutrients.

Although there was general acceptance that plant sap NO_3^- analysis can be a useful method for evaluating crop N status of vegetables, practical implementation of sap analysis was generally limited. One of the reasons is that the NO_3^- concentration can be affected by numerous factors, such as the type and age of the sampled plant part, individual N fertiliser applications and the time between sampling and analysis (Goffart et al., 2008). Strict sampling and handling protocols can appreciably reduce the effects of these factors (Goffart et al., 2008). An important issue influencing the use of sap analysis and other forms of plant analysis is the requirement for sufficiency or reference values that permit interpretation of results (MacKerron et al., 1995). These should be either determined or verified for given crops in given locations; however, at the moment there are few locally determined or verified sufficiency values available.

Currently, there is increasing interest in the use of sap analysis to assist with fertiliser management. Peña-Fleitas et al. (2015) showed that petiole sap NO_3^- concentration was very strongly related to crop N status of fertigated tomato and muskmelon. Additionally, the results of Peña-Fleitas et al. (2015) suggested that for fertigated tomato grown in very different conditions that very similar sufficiency values could be used.

In the Netherlands and Belgium, the use of plant sap tests (in some cases with leaf tissue) has been revitalised recently by some private consultancy agencies and commercial laboratories (Smits, 2008). In order to deal with the variability of nutrient concentration within plants and over time, and also possibly between cultivars, strict sampling and handling procedures are being used. For example, one private laboratory uses a procedure in which the top leaflet from the leaf at the flowering cluster and the leaf at the fifth cluster are sampled at two week intervals. This laboratory developed target values for the leaf NO_3^- concentration (and other nutrients) from empirical data. Using this approach, the composition of the fertigation nutrient solution, in particular the NO_3^- and K concentrations are adjusted in response to the two-weekly analytical results. Although this methodology appears to be strongly empirical without a clear scientific basis, it has been shown to be quite effective in that growers have been able to considerably reduce the amount of N applied whilst maintaining yields (W. Voogt, pers. commun., 2015). This method is growing in popularity, with both greenhouse and field vegetable growers in the Netherlands. A general difficulty with these and other private companies providing sap analysis is the secrecy regarding procedures and sufficiency values, which impedes scientific evaluation.

USE OF PROXIMAL OPTICAL SENSORS FOR N MANAGEMENT

While there is currently little use of proximal optical sensors for N management of commercial vegetable crops in Europe, the use of these sensors for crop N management is a very active research area. A considerable amount of research has been done using hand-held chlorophyll meters with vegetable crops (e.g., Farneselli et al., 2010; Gianquinto et al., 2011; Padilla et al., 2014, 2015); however, at the moment, there appears to be little use in commercial production. A promising line of work is the use of canopy reflectance sensors to assess crop N status. These sensors are being used to assist with N management of commercial cereal crops in North America and elsewhere to both determine N fertiliser rates and to automatically control variable rate application of N fertiliser (Meisinger et al., 2008). Studies with tomato and muskmelon have demonstrated the sensitivity of canopy reflectance to assess crop N status (Padilla et al., 2014, 2015). Padilla et al. (2015) reported a procedure to determine sufficiency values for fertigated vegetable crops.

USE OF SIMULATION MODELS AND DECISION SUPPORT SYSTEMS FOR N MANAGEMENT

In the last 20 years, there has been appreciable work in Europe to develop simulation models and computerised decision support systems (DSS) to assist with fertiliser management. These can be considered as having two broad classes: 1) the use of models for scenario analysis, and 2) DSS for determining fertiliser application rates.

The EU-Rotate_N model (Rahn et al., 2010) is a comprehensive scenario analysis tool that, for many vegetable species, simulates growth, marketable yield and N losses in response to climate, and crop, N and irrigation management. It considers N and water supplied by diverse sources. It can be used to conduct production, economic and environmental impact analyses. EU-Rotate_N was developed to be suitable for diverse vegetable production systems throughout Europe.

Numerous computer-based DSS have been developed to assist with fertiliser recommendations; mostly with N, but sometimes for other nutrients. Increasingly, these DSS can be used on tablets and smartphones. Some DSS are installed directly on the computing device, others are web-based. With DSSs, numerous and frequent calculations can be done rapidly, various inputs can be considered, stored data records can be used, and detailed records can be kept. Relatively simple DSS with few data requirements are most suitable for on-farm use (Rahn et al., 1996; Parneaudeau et al., 2009; Gallardo et al., 2014).

Two broad modelling approaches are used for DSS based on simulation models. “Static” models assume standard conditions, such as average climatic conditions and expected growth or yield. “Dynamic” models respond to real time or forecast conditions. Static DSSs require less input data because growth and yield are assumed. Data bases of long term average climate data can be incorporated. Dynamic DSSs more accurately simulate actual cropping conditions. Some DSS offer both approaches, e.g., Veg-Syst-DSS (Gallardo et al., 2014).

A number of DSSs based on simulation models have been developed in Europe to assist with N fertilisation of vegetable crops e.g., N-Expert (Fink and Scharpf, 1993; Feller, 2015), Azofert (Parneaudeau et al., 2009), WELL_N (Rahn et al., 1996) and VegSyst-DSS (Gallardo et al., 2014). 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 procedures used by N-Expert were described earlier in this article.

The most recent version of N-Expert (Fink and Scharpf, 1993), N-Expert 4 was released in September 2015 (Feller, 2015); information and a free download in English or German are available at: http://www.igzev.de/n-expert/?lang=en. N-Expert 4 is executable on all computer operating systems (as at September 2015). It assists vegetable growers and advisers/consultants to calculate the N (and also P, K and Mg) fertiliser requirements and to prepare N, P, K and Mg nutrient balances as required by the German Law. N-Expert 4 contains a database of nutrient uptake for numerous vegetable crops. N-Expert is used to develop fertiliser recommendations for German growers.

The WELL_N DSS (Rahn et al., 1996, 2010) 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. 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 south-eastern (SE) Spain (Gallardo et al., 2014). FERTIRRIGERE (Battilani et al., 2003) is DSS-based on a dynamic model that assists in irrigation and nutrient management of processing tomato grown in Mediterranean regions. There are other relevant European DSSs but there is not sufficient space to present them. A recommended approach is to combine the use of a DSS with monitoring methods (Granados et al., 2013).

CONCLUSIONS

Numerous approaches are used to assist with N fertiliser management in Europe. The most implemented are the various recommendation schemes of NW and Central Europe based on soil testing or estimated soil N supply. N balance calculations are widely used. There is some use of plant testing and decision support systems. Legislative pressure enhances the adoption of fertiliser recommendation schemes.

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