Sustainable irrigation and nitrogen management of fertigated vegetable crops

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Abstract

Fertigation in combination with drip irrigation is being increasingly used in vegetable crop production. From a nutrient management perspective, this combination provides the technical capacity for precise nitrogen (N) nutrition, both spatially and temporally. With these systems, N and other nutrients can be spoon-fed to crops, through frequent applications of small amounts, to the immediate root zone as required by the crop. In commercial farming practice, management of combined drip/fertigation systems generally does not take advantage of this potential for precise N management. As is common in commercial farming, management of both irrigation and N with drip/fertigation systems is generally based on growers' experience, with the objective of avoiding deficiencies that may limit production. Because of frequent N application, the established improved nutrient management strategies, based on infrequent soil testing, pre-plant and one or two side-dress applications, are of limited value. With drip/fertigation, dynamic N management approaches are required so that the capacity for frequent small applications can be fully exploited to provide (a) site and season specific management and (b) dynamic responses to temporal N requirements. Dynamic irrigation management is required for the same reasons. Modelling and monitoring approaches and combinations of the two enable exploitation of the technical capacity for precise N and irrigation management. Decision support systems (DSS) based on simple simulation models with limited data inputs can provide crop specific plans of daily N and irrigation requirements. The use of soil moisture sensors is an effective and proven monitoring approach for irrigation management. For monitoring of soil/crop N status, soil monitoring through regular sampling of soil-water extracts and soil solution is being used, and crop/plant monitoring approaches such as with proximal optical sensors and petiole sap analysis are promising methods.

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

INTRODUCTION

The area of vegetable crops grown with fertigation in combination with drip irrigation is continually increasing. Combined fertigation and drip irrigation is commonly used in important vegetable growing areas such as throughout southern Europe and in central California. The combined use of fertigation and drip irrigation provides the technical capacity to spoon-feed nitrogen (N) and irrigation as required by the crop. However, this technical capacity for precise N and irrigation management is generally not being taken advantage of. Despite the widespread use of combined fertigation/drip irrigation systems, major vegetable growing regions such as Almeria and Murcia in Spain (Thompson et al., 2007a) and in central California (Center for Watershed Sciences UC Davis, 2012) have increasing nitrate (NO_3^-) concentrations in aquifers.

Current N and irrigation management practices of vegetable growers are generally based on experience of "what works" in terms of reliably producing high yielding and

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profitable crops (Thompson et al., 2007a). Commonly, the N and irrigation supplied to vegetable crops are excessive to crop requirements (Thompson et al., 2007a). To achieve sustainable intensive management of vegetable production, it will be necessary to accurately match both the N and irrigation supply to crop requirements. This will have to be achieved within the context of intensive vegetable production systems which are characterized by variations in climatic zones, soil types, growing seasons, planting dates and cultivars. Consequently, there is a need to develop N and irrigation management programs and tools with the flexibility to deal with such variation.

This article will review management techniques that are either currently available or being developed to enable growers to take advantage of the possibilities offered by combined fertigation and drip irrigation systems for spoon-feeding N and irrigation to vegetable crops. Doing so will enable precise and sustainable N and irrigation management. This review will be restricted to fertigation of soil-grown crops. Different management approaches and tools will be reviewed in the context of sustainable intensification. Sustainable intensification requires optimal management of N fertilization and irrigation to ensure high yielding, profitable vegetable crops with minimal N losses to the environment and the highly efficient use of irrigation water.

FERTIGATION SYSTEMS

Types of fertigation systems

There are various types of fertigation systems in which nutrients are supplied to crop through the irrigation system. These can be broadly categorized as being: (1) simple fertilizer tanks, (2) manually-operated multi-tank systems, and (3) computer-operated multi-tank systems. Generally, with category 1 systems, fertilizer 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. Fertigation is most commonly used with drip irrigation, but can also be used with sprinkler irrigation.

Basic considerations with fertigation systems

Common to all fertigation systems used with drip irrigation systems is the fundamental requirement to avoid blockages of drippers and subsequent low application uniformity which affects both irrigation and nutrient application (Bar-Yosef, 1999). It is therefore important to use only completely soluble fertilizers. There is a wide variety of suitable single, binary or compound mineral fertilizers that are available. Several fertilizers can be combined but care must be taken to avoid mixing incompatible fertilizers (Bar-Yosef, 1999; Sonneveld and Voogt, 2009). Water quality, high solubility of fertilizers, effective filtration and pH control are all fundamental to avoid blockage of drippers. Maintaining a high uniformity of application of irrigation water is a fundamental requirement for optimal irrigation and N management with combined fertigation and drip irrigation systems.

NUTRIENT AND IRRIGATION MANAGEMENT CONSIDERATIONS WITH FERTIGATION SYSTEMS

The combination of fertigation with high frequency irrigation, such as drip irrigation, enables nutrients to be spoon fed to a crop as required. This provides the potential to match the application of N to the demand of the crop. Applying small frequent N applications reduces substantially the risk of N loss associated with larger, more infrequent N applications as occurs with traditional N management of a pre-planting application and commonly one or two side-dress application(s) (Figure 1). Management tools are required to ensure that the frequent supply of N and irrigation matches the requirements of the crop.

When applying nutrients by fertigation on the basis of rate, conventional agronomic nutrient management practices can be used, e.g., reducing the applied rate to consider available nutrients supplied by the soil. When applying nutrients on the basis of concentration to soil-grown crops, there are two general approaches. One approach is to use nutrient solutions formulated for soil-grown crops, as is the case in The Netherlands (Sonneveld and Voogt, 2009). Where there has not previously been such a research program, the composition of the nutrient solutions is commonly based on those of soil-less cropping. Generally, in commercial farming practice, the composition of the nutrient solution is fixed for individual phenological phases or throughout the crop. Adjustments may be made during the crop in response to visual observations e.g., the N concentration can be adjusted to influence the ratio of vegetative to reproductive growth and because of increasing fruit load (e.g., adjusting N:K ratio).

Commonly, apart from NO_3^- in irrigation water, other N sources such as soil mineral N in the root zone at planting and N mineralized from organic materials are not considered when formulating nutrient solutions (Thompson et al., 2007a) which contributes to excessive N application (Thompson et al., 2007a; Soto et al., 2015). Consequently, despite the technical capacity of fertigation/drip irrigation systems for precise N and irrigation management, these systems are commonly associated with excessive N application and the consequent likelihood of detrimental N loss to the environment (Thompson et al., 2007a; Soto et al., 2015). The Netherlands is an exception in that the soil N supply is often considered because of the widespread use of the 1:2 volume soil:water extract method (W. Voogt, 2015, pers. commun.). Despite there being economic and environmental reasons to optimize irrigation, commonly irrigation is not tuned to crop demand, and to reduce risk growers prefer to over- rather than to under-irrigate (Voogt et al., 2000; Thompson et al., 2007a).

Both irrigation and N management have to be separately optimized when using fertigation. (Voogt, 2004; Thompson et al., 2007a; Soto et al., 2015). Excessive irrigation when using an optimal N concentration results in excessive N application. Conversely, applying small volumes of irrigation (e.g., with young crops) at a fixed N concentration may result in insufficient N application (R.B. Thompson, unpublished data).

PRESCRIPTIVE AND CORRECTIVE MANAGEMENT FOR IRRIGATION AND NITROGEN

The recommended approach for optimizing both irrigation and N management of fertigated vegetable crops is a combination of prescriptive and corrective management (Giller et al., 2004) for both irrigation and N. Prescriptive management is the preparation of detailed plans of recommendations for both irrigation and N fertilizer applications. 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.

OPTIMAL IRRIGATION MANAGEMENT

Two general approaches are used for optimizing irrigation of vegetable crops: (a) estimation of crop water requirements based on crop evapotranspiration (ETc), and (b) the use of soil moisture sensors to assist in determining the timing and volumes of irrigation.

Estimation of crop water requirements

The generally accepted FAO approach estimates crop water (irrigation) requirements based on a previous calculation of ETc (Allen et al., 1998). Irrigation additional to ETc is applied to consider application efficiency and the salinity of irrigation water (Rhoades and Loveday, 1990). ETc is estimated from reference evapotranspiration (ETo) values derived from local climatic data (Allen et al., 1998) and locally-derived or general crop coefficient (Kc) values (Allen et al., 1998). FAO recommended equations (e.g., Penman Monteith; Allen et al., 1998) or local adaptations (Gallardo et al., 2013) are used to estimate ETo.

Water balance calculations are used to consider stored soil water and effective precipitation, and to assist with determining irrigation frequency. In greenhouses that crop in soil and use drip irrigation, it can generally be assumed that crop water requirements equal ETc because there is no rainfall and the soil water content is constantly close to field capacity (Gallardo et al., 2013). Ideally, locally developed software programs will be available to assist in the calculation of a detailed plan of irrigation requirements for frequently irrigated fertigated/drip irrigated crops.

For Dutch greenhouse horticulture, de Graaf and van den Ende (1981) developed a simple crop ETc model whose inputs were commonly available data in commercial greenhouse. This approach was subsequently improved and is now widely used for irrigation scheduling in commercial practice in The Netherlands (de Graaf, 1988; Voogt et al., 2000). While initially intended as a method to ensure optimal crop water status (Voogt, 2005), Voogt et al. (2006) showed that high water and nutrient efficiencies could be obtained in commercial practice.

Use of soil moisture sensors to assist with irrigation management

Soil moisture sensors enable irrigation management to be adjusted to the particular characteristics of individual crops and fields. The sensors and data interpretation can be managed by growers; web-based services are increasingly being used to assist with sensor management and data interpretation. Soil moisture sensors are useful tools for vegetable crops irrigated with high frequency drip irrigation systems where soil moisture is often maintained within a narrow range of soil moisture, close to field capacity, while simultaneously limiting drainage. Soil moisture sensors can be used as a “stand-alone” method, or can be combined with the FAO method for estimating crop water requirements. Such a combination enables growers to take full advantage of the technical capacity of high frequency drip irrigation systems to spoon-feed water to crops as required.

The current soil sensor technologies are described by Charlesworth (2005) and Pardossi et al. (2009). The use of these sensors for irrigation scheduling is discussed by Hanson et al. (2000), Thompson and Gallardo (2003), Evett (2007) and Pardossi et al. (2009). Sensors measure soil matric potential (SMP) or volumetric soil water content (VSWC). A useful and simple sensor, the “Full Stop sensor” can be used to determine when sufficient irrigation has been applied by indicating the arrival of the wetting front at a given depth (Charlesworth, 2005; Stirzaker et al., 2009).

Generally, for both SMP and VSWC sensors, lower limit or threshold values are used to identify when to irrigate and upper limit values to identify when irrigation is sufficient (Thompson and Gallardo, 2003; Gallardo et al., 2013). Most commonly, fixed irrigation volumes are applied; automatic control of the applied volume requires very frequent measurement with sensors that have rapid response times. Tendencies over time can be used to adjust irrigation volumes. Irrigation scheduling with SMP is relatively straightforward; lower limit SMP values for given crops are generally applicable for a range of soil types and conditions. Lower limit SMP values are commonly available in scientific and extension literature (e.g., Hanson et al., 2000; Locascio, 2005; Shock et al., 2007) or can be determined for crops in a given system (e.g., Thompson et al., 2007b). Commonly, lower limits of SMP for vegetable crop are >-50 kPa (Locascio, 2005; Thompson et al., 2007b). Adjustments to recommended lower limit SMP values may be required to consider evaporative demand and soil texture (Hanson et al., 2000; Locascio, 2005). Limits for VSWC need to be determined in situ or at least locally in representative conditions, by using dynamic protocols (Thompson et al., 2007c) or experimental procedures (Thompson et al., 2007b); relevant procedures are described by Charlesworth (2005) and Thompson et al. (2007c).

Issues related to the practical use of soil moisture sensors for irrigation management are discussed by Thompson and Gallardo (2003), Charlesworth (2005), Evett (2007), and Gallardo et al. (2013).

1. Soil matric potential sensors.

The two types of SMP sensors most suitable for drip irrigated vegetable crop are tensiometers and granular matrix sensors. Tensiometers are cheap, simple and easy to use. However, they require preparation and maintenance to provide accurate and reliable data (Thompson and Gallardo, 2003), which can be a major drawback for growers. The relatively narrow working range of most tensiometers of 0 to -80 kPa is generally adequate for frequently irrigated vegetable crops, but can be a limitation where soils dry out quickly. With vegetable crops receiving very frequent drip irrigation, it is possible to maintain SMP within this range, depending on soil type and climatic conditions. Tensiometers can be read manually or used with pressure transducers to automatically initiate irrigation.

Granular matrix (GM) sensors measure the electrical resistance between two electrodes in a porous matrix; the resistance being a function of the soil matric potential (Charlesworth, 2005; Thompson et al., 2006). The most commonly-used is the Watermark sensor (Irrometer Co., CA, USA). A hand-held reader can be used to supply the current, interpret the signal, and read values. Data can be input directly to an irrigation controller. GM sensors are cheap, simple, easy to install with little preparation and maintenance requirements. The measuring range is from -10 to -200 kPa. While they have a wider measurement range than tensiometers, they are inaccurate in wet soils (0 to -10 kPa) and have a slower response in soils that dry quickly (Thompson et al., 2006). In general, GM sensors are less accurate than tensiometers but require appreciably less attention.

Recently, SMP sensors based on Frequency Domain Reflectometry (FDR) technology (see VSWC sensors) have been developed. Examples are the MPS family of sensors (Decagon Devices, WA, USA) which provide measurement of SMP over a very wide working range (-9 to -100,000 kPa) and have no maintenance requirement. Limited data are available evaluating these sensors.

2. Volumetric soil water content sensors.

There is a large and constantly changing number of commercially available di-electric sensors that measure volumetric soil water content (VSWC). There are three general types of di-electric sensor: (i) Time Domain Reflectometry (TDR), (ii) Time Domain Transmissiometry (TDT), and (iii) capacitance, or Frequency Domain Reflectometry (FDR). There are various formats for VSWC sensors, stand-alone mode, connected to data loggers, or connected directly to irrigation controllers. TDR sensors, while widely used in research, are little used for irrigation management. TDT sensors are an adaptation of TDR sensors that are generally cheaper and more suitable for use in commercial farming. Capacitance sensors are widely used for irrigation management. Capacitance sensors are available in several different configurations e.g., probes of various cm length or rings mounted at various depths on a vertical probe (Thompson and Gallardo, 2003; Charlesworth, 2005).

VSWC sensors with frequent measurement and fast response times can be used to automatically initiate and stop irrigation. Sensitivity to changes in soil salinity has been reported for capacitance sensors (Thompson et al., 2007d), which can affect its use with vegetable crops where salinity is managed to increase fruit quality. It has been suggested that capacitance sensors with higher operating frequencies are less sensitive to salinity

(Regalado et al., 2010). When using VSWC sensors for irrigation scheduling, the determination of lower irrigation limits, i.e., when to irrigate, is not as straightforward as when using SMP sensors (Thompson and Gallardo, 2003; Thompson et al., 2007c; Gallardo et al., 2013). Different protocols to determine lower limits of VSWC for vegetable crops in soil were evaluated by Thompson et al. (2007c).

Some VSWC sensors also measure bulk soil EC (Gallardo et al., 2013). Simultaneous measurement of soil EC potentially can be used for soil salinity and nutrient management. Caution should be taken regarding bulk soil EC data since soil bulk EC data are difficult to interpret for practical salinity management, and conversions are required to obtain equivalent soil solution extract EC values (Gallardo et al., 2013). There are uncertainties regarding these conversions and they are an on-going area of research (Gallardo et al., 2013). While there are uncertainties regarding absolute soil solution EC values derived from bulk soil EC measurement, tendencies over time can assist with soil salinity and nutrient management of fertigated vegetable crops.

OPTIMAL NITROGEN MANAGEMENT

General

Numerous uncertainties influence the economically optimal N fertilizer rate, or concentration, at a given time, which is defined here as the minimum rate or concentration of N fertilizer required for maximum production. For a given species in a given region, the optimal N rate or concentration varies with site and growing conditions and crop development stage. The quantities of crop available N provided by (a) soil mineral N at planting, and (b) N mineralization from various organic sources (soil organic matter, soil amendments, crop residues) during the growing period, influence the optimal amount of supplemental N required as mineral fertilizer. Additionally, growing conditions (climate, season, planting date), crop management practices, and other site specific factors such as soil type and soil management influence the optimal rate/concentration of supplemental N. Generally, in commercial practice, excessive mineral N fertilizer is applied to avoid these uncertainties.

Optimal N management requires the appreciable reduction of these uncertainties, which can be achieved through the provision of viable information. Practical tools are required that provide quantitative information on (a) the expected crop N demand over time, (b) the expected soil N supply (from various sources), (c) the relationship of the soil N supply to crop N demand (deficient, sufficient, excessive), and (d) the amounts of supplemental mineral N fertilizer required, if any. Given the capacity of fertigation systems for very frequent N applications, and hence rapid correction of inadequate crop N status, this information should be provided at frequent time intervals.

The appropriate tools for a given crop/location will depend on the local availability of specific approaches and availability of support services (e.g., analytical laboratories, technical support), the crops being grown, the skills of the grower, and economic considerations. Increasingly, legislation is playing a role in forcing vegetable growers to adopt local recommendation schemes and technical tools, this tendency will continue. The main categories of available tools for N management, for use with fertigated crops, are: (1) soil testing approaches, (2) the Dutch 1:2 volume soil:water extract method, (3) soil solution analysis, (4) N balance calculations, (5) Decision Support Systems, and (6) crop/plant testing approaches.

Soil testing approaches

With soil testing approaches, the N fertilizer rate is adjusted in response to the amount of soil mineral N in the root zone. These can be considered as site specific approaches. Soil analysis methods are commonly used with open field cereal and vegetable crops.

In north-western and central Europe, the N_{min}, KNS and N-Expert methods are commonly used for N fertilizer recommendations for vegetable crops. Common to the three methods is the "N target value" which represents the required total mineral N supply.

Nitrogen supplied by the soil is subtracted from the "N target value" to calculate the mineral N fertilizer application rate. The N_{min} method, which is the simplest of the methods, only estimates a single rate for the entire crop, and therefore is not suitable for fertigated crops.

The KNS method is based on the amount of soil mineral N content throughout a crop and crop N uptake (Ziegler et al., 1996). Soil mineral N is determined at planting and at least once during the crop. It is assumed that there is a minimum buffer value of root zone soil mineral N below which production is N limited; buffer values vary with species and time. The buffer value is added to the anticipated N uptake for a given period (e.g., several weeks) to calculate the N target value for that period. Crop N uptake curves with short time intervals (e.g., weekly) are used. The soil mineral N present, at each sampling, is subtracted from the calculated N target value, for the next period, to calculate the amount of N fertilizer to apply. Commonly, N mineralization is also included in the soil N supply, most simply by assuming a fixed rate of N mineralization, often a value of 5 kg N ha^{-1} $week^{-1}$ (Feller and Fink, 2002). The KNS is essentially a N balance method (described subsequently). Based on the calculation of crop N uptake over short time periods (weekly, daily) and subsequent calculation of N fertilizer requirements for short time periods, the KNS method could be adapted for use with fertigated vegetable crops.

The N-Expert System is a computer-operated Decision Support System (DSS) which is a further development of the KNS system. It is the recommended system for estimating N fertilizer recommendations for vegetable crops in Germany. The N-Expert system, published by Fink and Scharpf (1993), calculates N target values from crop N uptake, a buffer value of root zone soil mineral N, and N mineralization using the modeling approach described by Feller and Fink (2002). Compared to the KNS system, N-Expert more effectively adapts N target values to specific field conditions; it incorporates a database of crop N uptake curves, considers yield variation and always considers N mineralization. As with the KNS system, N- Expert calculates the amount of N to be applied as mineral fertilizer, for a given period. As it can calculate N recommendations for specific periods, N-Expert could be adapted for use with fertigated crops. The N-Expert system will also be discussed in the section on Decision Support Systems.

The Pre Side-dress Nitrate Test (PSNT) used in the USA and Canada measures root zone soil NO_3^- during the crop immediately prior to the main side-dressing N application (Meisinger et al., 2008) and has been recommended for vegetable crops (Hartz, 2003, 2006; Hartz and Bottoms, 2009). Its primary use is to decide if side-dress N fertilizer is required (Meisinger et al., 2008); although Hartz and Bottoms (2009) suggested a procedure to calculate the rate of fertilizer N when additional is required. Given that it is used for single side-dress applications, it is not suitable for determining amounts of frequently-applied N for fertigated vegetable crops. To be used for fertigated crops, more frequent soil analysis would be required.

Dutch 1:2 soil:water extract method

For soil-grown crops in high technology greenhouses in The Netherlands, fertigation is standard practice, and species specific fertigation programs have been developed (Sonneveld and Voogt, 2009) and are commonly used by commercial growers (W. Voogt, 2015, pers. commun.). The fertigation programs are based on a standard nutrient solution, for a given species, to which adjustments are made for specific conditions such as water quality, cropping stage, and soil type. Since Dutch greenhouses are characterized by continuous cropping, basal fertilizer dressings are limited to phosphate and occasionally Mg and K fertilizers. N is supplied solely by fertigation and the applied N concentration supplied is controlled by continuous measurement of the nutrient solution EC, which is also used as an important growth management tool (Sonneveld and Voogt, 2009).

Because of frequent nutrient addition with fertigation, interest is in the immediately available nutrients in the soil, rather than the nutrient supply over longer time periods. To optimize the management of frequent nutrient addition, relatively frequent testing may be used, which requires simple and quick procedures to obtain and prepare samples. Composite soil samples are taken regularly, and extracted and analyzed using the 1:2 volume (soil:water) extract method (Sonneveld and Van den Ende, 1971; Sonneveld et al., 1990; Sonneveld and Voogt, 2009) which provides a good estimate of the [NO_3^-] in the soil solution and of total amount of 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 et al., 1990; Sonneveld and Voogt, 2009). The analytical results of the extract solution are compared with target values and limits for individual nutrients, and also for Na, Cl, pH and EC. 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 The Netherlands for a number of years (W. Voogt, 2015, pers. commun.), and recently has been adopted by numerous greenhouse growers in Italy (L. Incrocci, 2015, pers. commun.) and Greece (de Kreij et al., 2007). In Italy, use of the 1:2 (soil:water) extract method is facilitated by a user-friendly software (GreenFert; http://www.cespevi.it/softunipi/greenfert.html) developed by L. Incrocci and colleagues at the University of Pisa (L. Incrocci, 2015, pers. commun.). The sufficiency range values determined for crops in Italy are somewhat lower than those used in The Netherlands (L. Incrocci, 2015, pers. commun.).

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 to be an issue with very localized measurements such as ceramic cup suction soil solution samplers (Hartz, 2003). While most use of the 1:2 volume (soil:water) extract method in The Netherlands and in Italy has been with soil-grown greenhouse crops, it can be used with open field fertigated vegetable crops (W. Voogt, 2015, pers. commun.).

Soil solution analysis

Ceramic cup suction soil solution samplers can be used for N management of fertigated vegetable crops by regularly sampling the soil solution in order to control the soil solution [NO_3^-] in the immediate root zone. This method is well-suited for use with vegetable crops receiving frequent nutrient addition through combined fertigation and drip irrigation. In Israel, soil solution samplers are commonly used in commercial vegetable production using a minimum threshold value of 5 mmol L^{-1} (S. Kramer, Israeli Ministry of Foreign Affairs, 2016, pers. commun.). Hartz and Hochmuth (1996) suggested their use in vegetable crops with a minimum threshold value of 5 mmol L^{-1}. Later Hartz (2003) commented that the high spatial variability of soil solution [NO_3^-] may limit their practical value. 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^-] (Gallardo et al., 2006; Granados et al., 2013; Peñ a-Fleitas et al., 2015). These results suggested that an on-going tendency of increasing soil solution [NO_3^-] is a sensitive 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 the uncertainties associated with spatial variation of individual point measurements, which can be relatively more important with commercial growers than in research studies because of grower reluctance to have a sufficient number (e.g., four) of replicated samplers within a field.

In greenhouse-grown pepper, Granados et al. (2013) maintained soil solution [NO_3^-] within a sufficiency range of 8-12 mmol L^{-1} as part of an improved management system that appreciably reduced NO_3^- leaching and N fertilizer use. Subsequent studies have suggested that minimum thresholds values can be lower (R.B. Thompson, 2015, pers. commun.). Through replication and careful selection of representative locations, the average coefficients of variation (CV) reported by Granados et al. (2013) were 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).

Small portable “quick test” systems (Thompson et al., 2009; Parks et al., 2012) enable on-farm determination of the $[NO_3^-]$. With rapid analysis system, considerable care must be taken and results should be periodically checked against laboratory analysis. Combining the use of the suction samplers with on-farm use 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 fertilization of fertigated vegetable crops through increasing tendencies. Excessive N fertilization is the most common N fertilization issue in intensive vegetable production. Given the current uncertainties associated with definition of sufficiency ranges, it is suggested that other approaches (e.g., plant testing) be used to accurately determine N insufficiency. As a general rule, with soil solution $[NO_3^-]$ of >5 mmol L^{-1} it is likely that the immediate N supply will not limit crop growth.

N balance calculation

The N balance calculates the amount(s) of mineral N fertilizer to be applied for an entire crop or for periods within a crop. The determination of N fertilizer application amount using N balance calculations has the advantage of explicitly considering all major N inputs such as crop available N supplied by the soil. In its simplest form, N balances are calculated for the duration of a crop. With the use of simulation models, 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. Additional soil analyses can be used as feed-back to adjust parameters. The commonly-used N inputs and outputs are listed in Table 1.

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

N Inputs	N outputs
Initial soil mineral N ($N_{min-ini}$)	Crop N uptake (N_{crop})
N mineralized from soil OM ($N_{minz-OM}$)	N losses (N_{loss})
N mineralized from org. residues ($N_{minz-res}$)	Final soil mineral N ($N_{min-fin}$)
Mineral N fertilizer (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 fertilizer, using the general approach of Equation 1:

$$N_{fert} = N_{outputs} - N_{inputs} \text{ (apart from } N_{fert}) \quad (1)$$

There are various approaches to 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), this ensures that soil mineral N is not limiting 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 equation:

$$N_{fert} = (N_{min-ini} + N_{min-OM} + N_{minz-res})] - (N_{crop} + N_{Buffer\,min} + N_{Immobilization}) \quad (2)$$

where $N_{Buffer\ min}$ is the buffer amount of soil mineral N and $N_{Immobilization}$ is an estimate of N immobilization calculated as $(N_{crop} + N_{Buffer\ min}) \times 0.15$.

Another approach is to calculate N fertilizer requirements by estimating the apparent recovery or efficiency (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 immobilization are implicitly considered as being the N not recovered by the crop. Crop fertilizer requirements can be calculated using the equation: N_{fert} =

$$(1/E) * [N_{crop} – (N_{min\text{-}ini} + N_{min\text{-}OM} + N_{minz\text{-}res})] \quad (3)$$

N balance calculations form part of the KNS and N-Expert systems and are used in a number of Decision Support Systems (DSS) as discussed subsequently. Frequent N balance calculation as done in some DSS can be used to make frequent N recommendations that are suitable for fertigated vegetable crops.

Decision support systems (DSS)

Computer-based DSS can be used to calculate N fertilizer recommendations, and also crop irrigation requirements; the same DSS can be used to calculate both N fertilizer and irrigation recommendations e.g., FERTIRRIGERE (Battilani et al., 2003) and VegSyst-DSS (Gallardo et al., 2014). The term "computers" here also refers to smartphones and tablets. These DSSs can be stand alone or web-based programs. The use of computer technology enables numerous and frequent calculations to be made, numerous inputs to be considered, the use of stored data records, record keeping and the inclusion of simulation models. Frequent calculation is essential for fertigated vegetable crops with frequent nutrient application. DSSs come with varying degrees of complexity. Relatively simple DSS with few data requirements are well-suited for on-farm use (Parneaudeau et al., 2009; Gallardo et al., 2014).

Several DSSs based on simulation models and N balance calculations have been developed in Europe to assist with N fertilization in vegetable crops e.g., N-Expert (Fink and Scharpf, 1993), Azofert (Parneaudeau et al., 2009), and the VegSyst-DSS (Gallardo et al., 2014). In these DSS, a simulation model or data base is used to provide detailed crop N uptake which is subsequently used in N balance calculations. The VegSyst-DSS (Gallardo et al., 2014) makes daily N balance calculations.

DSSs to assist with N management have been developed using simulation approaches other than the N balance. The WELL_N DSS (Rahn et al., 1996) has been used for making N recommendations for field vegetable production in England. Another approach employing simulation models to assist with N (and irrigation) management is the use of simulation models for scenario analysis. EU-Rotate_N (Rahn et al., 2010) is a useful and comprehensive scenario analysis tool that has been used in diverse vegetable cropping systems (e.g., Guo et al., 2010; Soto et al., 2014). It enables assessment of the agronomic and environmental consequences of different management scenarios. The "Fertigation model" (Voogt et al., 2000) was specifically developed for soil-grown greenhouse crops and calculates crop N demand by continuous computation of the N uptake concentration.

Two broad modelling approaches are used with DSS based on simulation models. They can be either "static" in which standard conditions are assumed such as expected yield and average climatic conditions, or they can be "dynamic" in that they are based on real time or forecast climatic data. Static approaches require less data input as assumed yields and data bases of long term average climatic data are used. Dynamic models use simulation models in the context of actual cropping condition and which can respond to unseasonal weather and to weather fluctuations. Generally static models will require less data input. Some DSS use both approaches, giving the user the option of using a data base of average long term climatic data or entering real time climatic data as in the VegSyst-DSS (Gallardo et al., 2014).

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, pers. commun.).

The VegSyst-DSS (Gallardo et al., 2014) was prepared specifically for fertigated vegetable crops, grown in greenhouses. This DSS contains the VegSyst simulation model which simulates crop N uptake and crop evapotranspiration (ETc). The VegSyst-DSS calculates N fertilizer requirements based on crop N uptake and by considering soil mineral N, and N mineralized from both manure and soil organic matter, and the efficiency with which N from each N source is used (Gallardo et al., 2014). It calculates crop water requirements by considering irrigation application efficiency, irrigation water EC and ETc. For each day it calculates the applied N concentration and irrigation volume. In the working program of the VegSyt-DSS (http://www.ual.es/GruposInv/nitrogeno/VegSyst-DSS.shtml), the N concentration is averaged over four weeks to avoid excessively frequent adjustment.

For fertigated, open field, leafy vegetables grown in the central coast of California, the on-line DSS software CropManage (https://ucanr.edu/cropmanage/login/offline.cfm, click on "About CropManage") has been developed to estimate both irrigation and N fertilizer requirements on a field-by-field basis (Cahn et al., 2013). The N fertilizer algorithm generates N fertilizer recommendations based on estimated crop N uptake, current soil NO_3^- content, and estimated soil N mineralization. The irrigation scheduling algorithm uses real- time reference evapotranspiration data, crop coefficients based on the planting configuration, and soil water holding characteristics. 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 g^{-1}, based on the philosophy of the PSNT (described previously).

The "Fertigation model" of Voogt et al. (2000) combines a crop evapotranspiration model with an empirical nutrient uptake model. It calculates the on-going uptake concentrations (Thompson et al., 2013) 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. The output is the composition of the nutrient solution which is used as input for the computer operated fertigation unit.

Crop and plant monitoring approaches

Monitoring of crop or plant N status potentially can provide information on the adequacy of the N supply in relation to the N demand (Schröder et al., 2000). While total N analysis of leaf tissue is an established method, it is not well suited to frequent monitoring of fertigated vegetable crops. This is because of the logistics of sending samples to analytical laboratories, the time delay in obtaining results, and the reported limited sensitivity to recent changes in crop N status (Olsen and Lyons, 1994). This review will be restricted to methods that can be used frequently and quickly to assess crop N status of fertigated vegetable crops, thereby permitting rapid correction.

1. Petiole sap NO_3^- analysis.

Petiole sap [NO_3^-] has been proposed as an indicator of current crop N status of vegetable crop. Strict protocols are required for sampling, handling and storing of the plant material (petioles), and for the extraction and storage of sap samples (Goffart et al., 2008; Hochmuth, 1994, 2012). Analysis can be made rapidly, on the farm, using quick test systems (Thompson et al., 2009; Hochmuth, 1994, 2012; Parks et al., 2012). With rapid analysis systems, considerable care must be taken and results should be periodically checked against laboratory analysis.

Sufficiency ranges for a number of important vegetable species, at different phenological stages, have been published for Florida, USA (Hochmuth, 1994, 2012), but otherwise there is limited data of sufficiency ranges and values that are publicly available. Generally, the values of the sufficiency range decline as the crop grows, and recommendations are given for specific phenological stages (Hochmuth, 1994, 2012). Hartz and Bottoms (2009) demonstrated the importance of having appropriate sap [NO_3^-] ranges and values, without which correct interpretation is not possible. Sap [NO_3^-] values can be affected by factors such as cultivar, amount and timing of N previous application, and crop water status (Goffart et al., 2008). Given such sensitivity to various factors, it is generally considered that sap NO_3^- analysis be used for specific combinations of regions and cropping systems, with each combination having its own sufficiency ranges/values for each species (Goffart et al., 2008). For example, the results of Farneselli et al. (2014) suggested that petiole sap [NO_3^-] was a good indicator of crop N status for processing tomato in central Italy.

Recent studies with fertigated tomato and muskmelon crops (Farneselli et al., 2014; Peña-Fleitas et al., 2015) have suggested that fertigated crops receiving frequent N application can: (a) maintain sap [NO_3^-] throughout much of the crop while N is being frequently applied, and (b) maintain strong and similar linear relationships between petiole sap [NO_3^-] and crop N status assessed as the Nitrogen Nutrition Index (NNI; Lemaire et al., 2008) throughout individual crops. Additionally, these studies suggested that similar relationships between sap [NO_3^-] and NNI were observed in different tomato crops grown in very different conditions, and that a common sufficiency value could be derived for much of the growth cycle of different tomato crops grown under very different conditions. These results suggest that petiole sap [NO_3^-] may behave very differently in crops receiving very frequent N application by fertigation compared to crops receiving traditional pre-plant and side-dress N applications. They further suggest that with fertigated crops, petiole sap [NO_3^-] sufficiency values and ranges can be relatively constant throughout much of a crop cycle, and that sufficiency values and ranges may be common for a given species grown under different conditions. Further work is required to fully examine the potential for using sap NO_3^- analysis for monitoring crop N status of vegetable crops grown with high frequency N application through combined fertigation and drip irrigation systems.

Recently, commercial laboratories in The Netherlands have developed rapid services for plant sap testing from which the analytical results are available within 2-3 days (W. Voogt, 2015, pers. commun.). Companies in south-eastern Spain are also providing these services (R. Thompson, 2015, pers. commun.). Growers have used this method to monitor and control the N-supply and have been able to considerably reduce the amount of N applied (W. Voogt, 2015, pers. commun.). These results are promising but require validation.

2. Chlorophyll meters.

Chlorophyll meters (CMs) are small, hand-held, clip-on optical sensors that indirectly measure leaf chlorophyll which is correlated to leaf N content. CM readings have been reported to be sensitive to crop N status (Goffart et al., 2008; Padilla et al., 2014, 2015). There are several commercially available sensors; most work has been done with the SPAD-502 (Konica-Minolta, Tokyo, Japan) and the Hydro N-tester (Yara International, Oslo, Norway). Given their ease of use, relatively low cost, suitability for frequent measurement, and general sensitivity to crop N status of vegetable crops (Goffart et al., 2008; Padilla et al., 2014, 2015), these sensors appear to have potential for use with fertigated vegetable crops. In general, it appears that they are likely to be most effective when used with a specific species in a specific region (Goffart et al., 2008). It is notable that after >20 years of considerable research there appears to be little evidence of their use for N management with commercial crops of any kind.

3. Canopy reflectance sensors.

In recent years, there has been considerable research on the use of proximal canopy reflectance sensors to assist with crop N management of diverse crop species (e.g., Fox and Walthall, 2008; Meisinger et al., 2008; Samborski et al., 2009). While most of this research has been conducted with cereal crops (Fox and Walthall, 2008; Meisinger et al., 2008; Samborski et al., 2009), there have been some studies with vegetable crops (e.g., Gianquinto et al., 2011; Padilla et al., 2014, 2015). Canopy reflectance sensors are being used for N management on commercial cereal farms, particularly for variable rate fertilizer application. Most of the sensors being currently used (e.g., Crop Circle and Greenseeker sensors) are active sensors with their own light source and which can be used in any light conditions. The big advantage of proximal reflectance sensors is that they measure large representative areas because of the large measurement window and continual measurement.

Canopy reflectance measurements are based on the interaction of different visible and

NIR (near infra-red) wavelengths with the crop canopy (Fox and Walthall, 2008; Samborski et al., 2009). The reflectance of 2-3 individual wavelengths is used to derive mathematical indices. There are numerous indices; the most commonly used is the NDVI (Normalized Difference Vegetation Index). A commonly-used procedure to interpret these data is to compare measured indices with N rich areas in which N is not limiting (Fox and Walthall, 2008). However, this implies that, when crop N status is excessive, sensor readings have a plateau response; this was not observed with muskmelon (Padilla et al., 2014) suggesting that it is not common to all vegetable species. The development of protocols to interpret data reflectance and other optical sensors to assess crop status and to determine N fertilizer application rates is currently a very active area of research (e.g., Meisinger et al., 2008; Samborski et al., 2009; Padilla et al., 2015). Padilla et al. (2015) suggested an approach for fertigated vegetable crops.

Canopy reflectance sensors are a promising approach for evaluating crop N status of fertigated vegetable crops. However, unlike with cereal crops, relatively little research has been done with vegetable crops and more research is required to ascertain their effectiveness with vegetable crops and to develop effective protocols for their use in commercial farming. Their capacity for frequent, rapid and representative measurement and their current use in commercial cereal crops suggest that these sensors have considerable potential for use with fertigated vegetable crops.

Recommended tools and approaches for optimal N management of fertigated vegetable crops

As previously mentioned, the recommended general approach for optimizing N management of fertigated vegetable crops is a combination of prescriptive and corrective management. Optimal prescriptive N management must consider all N sources and the crop N demand; this is best done using a N balance approach given that there is information available to assist in the accurate estimation of the various terms. We suggest that the ideal prescriptive management tool is a DSS that calculates a daily N balance with simulation of daily crop N demand; measured soil mineral should be a required input, and all other major N inputs should be considered. Optimal corrective N management can be done through the use of the Dutch 1:2 volume (soil:water) method or by sampling the soil solution with suction samplers. The latter is particularly useful for detecting excessive N application; the former requires adaptation to a given cropping environment. Two crop/plant monitoring approaches, sap analysis and canopy reflectance sensors are potentially useful corrective management tools for fertigated vegetable crops; however, further research and development work are required.

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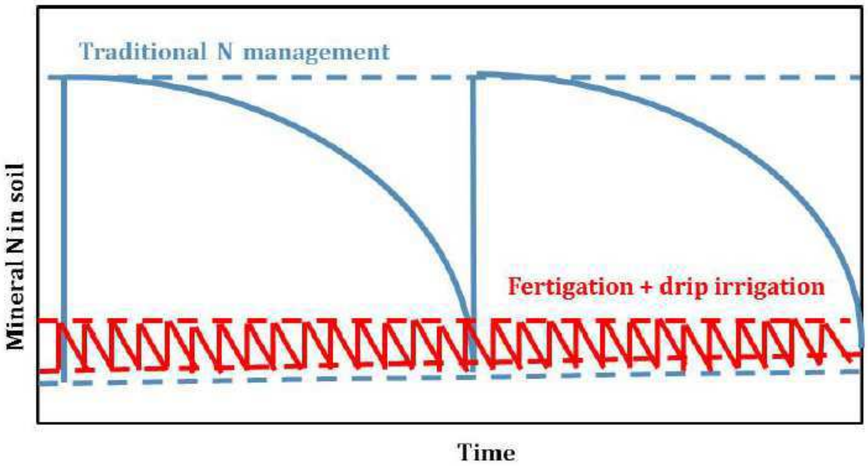

Figure 1. Schematic representation of the fluctuations with time of soil mineral N in the root zone associated with traditional N management and with frequent N application through combined fertigation and drip irrigation.