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# Decision support systems and models for aiding irrigation and nutrient management of vegetable crops

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ABSTRACT

Vegetable growers in Europe are continually under increasing pressure to optimize irrigation and nutrient management. This results from the widespread effects of climate change and of competition from other sectors for water, and increasing societal pressure to reduce nutrient contamination of water bodies. The widespread and growing adoption of drip irrigation and fertigation provides vegetable growers with the technical infrastructure for greatly improved irrigation and nutrient management. However, quantitative decisions to achieve optimal irrigation and nutrient management, and increasingly of the two together, require complex decision-making. Numerous factors regarding climate, soil characteristics, field infrastructure, and crop characteristics need to be considered. Decision Support Systems (DSSs) and simulation models are tools that process large and diverse amounts of information to provide irrigation and nutrient recommendations that are specific to individual crops and sites. Commonly, DSSs incorporate simulation models, which enables site and crop specific assessment, and the possibility for dynamic responses to fluctuations in climate etc. There is an on-going trend for web-based DSSs that can access on-line data bases such as of climate and soil data, and that users consult with smartphone Apps. This article firstly reviews several general aspects regarding the use of DSSs/models in commercial vegetable production, such as how to enhance their user-friendliness. Subsequently, it describes DSSs/models that have been developed or are being used to assist with irrigation or nutrient management, or both, of vegetable crops. The most relevant aspects of these DSSs/models are highlighted. In addition to DSSs/models for practical on-farm management, the use of DSSs/models for scenario analysis to demonstrate theoretical case studies to policy makers, growers and advisors is discussed. A focus throughout is on how to make these products attractive and effective to potential users. The geographical focus is on Europe; however, particularly relevant cases from elsewhere are also considered. With the current state of Information and Communication Technology (ICT), and considering the inevitable future developments, DSSs can provide vegetable growers with effective and user-friendly tools to assist them to optimize irrigation and nutrient management.

## 1. Introduction

Intensive vegetable production systems in Europe require appreciable inputs of nitrogen (N), and commonly, of irrigation to ensure high and profitable levels of production. With on-going climate change, there is an increasing requirement for irrigation of vegetable crops in temperate climatic regions, e.g. in northwest Europe, where previously irrigation was not required. There is increasing competition between different economic sectors for the limited supplies of fresh water, throughout Europe. This is particularly strong in southern Europe where there is strong competition with the tourist, domestic and industrial sectors for the limited fresh water supply (Gallardo et al., 2013). In these drier regions, there is often a diminishing supply of good quality water suitable for irrigation. This is a consequence of issues such as aquifer depletion, intrusion of sea water, and soil and aquifer salinization. Consequently, vegetable growers are under increasing pressure to manage irrigation water as efficiently as possible (Cahn and Johnson, 2017; Fereres et al., 2003).

Vegetable growers are also under increasing pressure to use N fertilizer inputs as efficiently as possible. Vegetable crops are particularly susceptible to having low N uptake efficiencies, i.e. the percentage of applied fertilizer N that is recovered by the crop (Thompson et al.,

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2017; Soto et al., 2015; Gallardo et al., 2020). Low N uptake efficiencies are generally associated with N losses to the environment and subsequent negative environmental impacts. Certain general characteristics of vegetable cropping contribute to the low N uptake efficiencies, these being shallow rooting, wide row spacing, and the short growing cycle of many species (Thompson et al., 2017). Given the general tendency to apply excessive N, to ensure that N is not limiting production, appreciable losses of N to the environment commonly occur (Thompson et al., 2007). Given that irrigation is also generally applied in excess, appreciable nitrate ($NO_3^-$) leaching loss commonly occurs in vegetable production. Consequently, intensive vegetable production is often associated with $NO_3^-$ contamination of underlying aquifers and with eutrophication of adjacent surface water bodies (Ramos et al., 2002).

In Europe, many areas with intensive vegetable production have been declared to be Nitrate Vulnerable Zones (NVZ) in accordance with the EU Nitrate Directive (Anonymous, 1991). In NVZs, vegetable growers, and other farmers, are required to improve N and irrigation management in order to reduce regional $NO_3^-$ leaching loss (Thompson et al. (2020)). Additionally, consumers are increasingly demanding vegetable products be produced with minimal negative environmental impacts. Appreciable reduction of $NO_3^-$ leaching requires improvements in both irrigation and N management (Thompson et al., 2017; this issue).

Numerous quantitative decisions have to be regularly made throughout a crop to achieve appreciably improved irrigation and nutrient management; commonly, each requires complex decision-making. With the on-going adoption of fertigation, irrigation and nutrient management are increasingly combined. For optimal irrigation and nutrient management, generally, numerous factors regarding climate, soil and crop characteristics, and field infrastructure need to be considered. Decision Support Systems (DSSs) are tools that can process large and diverse amounts of information to provide irrigation and nutrient recommendations for vegetable production. Commonly, these DSSs incorporate simulation models, which enables site and crop specific assessment, and the possibility for dynamic responses to fluctuations in climate etc.

This article firstly reviews several general aspects of DSSs used or intended for use in commercial vegetable production. Secondly, it describes DSSs developed, or in use, to assist with irrigation or nutrient management, or both, of vegetable crops. Throughout the article, a major focus is the identification of features and characteristics that enhance the effectiveness, practicality, ease of use, and adoption of these DSSs in the context of commercial vegetable farming.

## 2. Models and decision support systems – general considerations

### 2.1. Definition of models and decision support systems

A simulation model is a mathematical representation of a system. In the context of this article, we refer to a crop simulation model as a representation of a given crop that grows in a particular soil and climate. In crop models, the system (“the real crop”) is separated into components (e.g. crop, soil, and climate) and major processes are characterized using mathematical equations. Models can be used for research applications, for scenario analysis or for crop management. Complex mechanistic models are used in research, as a way to aggregate knowledge or to supplement costly field experimentations. Another application of models is to demonstrate, to farmers or policy makers, the impact of management practices on a crop or the environment.

A Decision Support System (DSS) is a computer-based information system that supports decision-making activities, typically providing recommendations. An effective DSS is an interactive software package that can assist farmers, advisors or administrators to make decisions that require the synthesis of numerous and diverse data. Generally, DSSs incorporate one or more simulation models that enable the preparation of recommendations that consider crop and site specific factors such as climate, planting dates, soil types, characteristics of irrigation system etc. DSSs commonly are software packages that include one or more simulation models, and communication tools to manage inputs and outputs. Among systems for data acquisition, there may be connection with (a) specific web services (e.g. satellite imagery, real time, forecast and retrospective climate data, soil data, crop characteristics) and (b) sensors providing real time data (e.g. climate, soil moisture). Model-based DSSs with sensors or tools allows users to verify the model prediction and to refine recommendations. Nutrient management DSSs can also include sub-models for nutrient recommendation schemes (Thompson et al., 2017; Tei et al., this issue) and can consider data from approaches used for crop and soil monitoring Padilla et al. (2020).

### 2.2. The complexity issue

An important issue when developing models and model-based DSSs for practical crop management is the level of complexity of the simulation models. Increasing complexity generally enhances the accuracy of simulation. However, it can reduce the likelihood of adoption by increasing data entry requirements. Traditionally, there has been perceived to be a trade-off between the accuracy of a DSS or simulation model and its practicality. This is because growers and advisors have very limited time and are unwilling to spend much time when using a DSS. Consequently, these potential users require simple, easy-to-use interfaces, and a reduced number of manual data inputs.

Recent developments in accessing data from on-line databases (climate data, soils data) and from sensors (e.g. climate, soil, plant) are means by which models can retain complexity and accuracy while maintaining limited manual data input by users. Simulation models that are integrated into DSSs must either (a) be relatively simple with a small number of relatively available inputs, or (b) be simple to use but with the capacity obtain inputs from on-line data bases and from sensors to achieve the higher level of complexity required to enhance the accuracy of simulation.

### 2.3. Calibration and validation

To ensure the accuracy of simulations by stand-alone simulation models or those that are components of DSSs, calibration and validation of the simulation model for the crop species and cropping conditions are required. Calibration is required to adjust model coefficients to the specific characteristics of the crop species and growing conditions. Validation verifies the performance of the calibrated model against measured values. Validation should be carried out with data sets different from that used for calibration, and from a different location. Ideally, once the validated models have been incorporated into the DSSs, they should be (i) evaluated under the commercial field conditions for which were designed for, and (ii) compared to local growers' practices to assess their benefit (e.g. water and/or fertilizer saving, economic return) (Mirás-Avalos et al., 2019).

### 2.4. Temporal context when using DSSs/models

For irrigation and/or fertilizer management, the DSSs/models can be used either to (a) prepare a plan for irrigation and/or fertilization before a crop, (b) prepare recommendations in real time during crop growth, or (c) prepare recommendations for the short-term future. The temporal nature of DSS/model operation depends on the type of climate data supplied to the model. Climate data drives many of the simulations of crop and soil processes. Historical climate data (i.e. long term average data) can be used for the preparation of plans for an entire crop prior to planting the crop. For management in real time, climate data measured in real time on the farm or obtained from climate network services are used. These calculations are actually retrospective (often for the most recent several days) because they are based on restoring a water deficit that has accumulated since the previous irrigation. For recommendations for the short-term future, forecast weather data can be used to estimate management requirements (e.g. irrigation volume, nutrient amounts) for a subsequent period of several days. The use of historical climate data is suitable in conditions were there is limited inter annual variability such as inside Mediterranean greenhouses (Gallardo et al., 2013).

### 2.5. *Computing environment – "stand-alone" or web-based systems*

Decision Support Systems (DSSs) can be either "stand-alone" systems where the program is installed directly on the computing device (e.g. computer, smart phone and tablet), or web-based programs that can be consulted, wherever there is an Internet connection, through a smartphone, tablet etc. The use of computer technology, either in stand-alone or web-based modes, enables numerous and frequent calculations to be made, various inputs to be considered, the use of stored data records for field and of databases, and record keeping. Web-based programs have practical advantages over stand-alone programs. Users can access information from different handheld devices, directly in the field and by different users from the same enterprise. Both stand-alone and web-based DSSs that use real time data require that data be input from sensors and/or data bases on a regular or continuous basis.

The current generation of DSSs for assisting with irrigation and nutrient management of crops, are increasingly web-based with access from computers, tablets or smartphones. They commonly have automatic retrieval of climate data from on-line data bases or climate stations. They also can be used to work with remotely sensed data and Geographical Information Systems (GISs) where required (Acutis et al., 2010). Smartphone Apps are a very effective method to access web-based DSSs, and are now commonly used. Smartphones are always with the user, and commonly the signal of the phone network enables continuous accessibility in the field and other locations. With Smartphone Apps, users can be immediately notified of issues requiring attention.

### 2.6. *Static and dynamic approaches*

Two broad modelling approaches are used for simulation models that are incorporated into DSS. 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 quickly to real time or forecast conditions. Static approaches require less input data because growth and yield are assumed; data bases of long term average climatic data can also be 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 fluctuations in actual climatic conditions. The use of long term average climatic data considerably simplifies the process of data entry; however, with the rapid developments in Information and Communication Technology (ICT) it is feasible to automatically enter real-time and forecast climate data (e.g. from 5 to 7 day forecasts). Where high frequency nutrient application is employed (e.g. with fertigation/drip irrigation), this enables N fertilizer planning for weekly periods to be based on real-time and forecast climate conditions. It also enables adjustment of previous provisional plans based on long-term average climatic data. DSSs that provide output used subsequently for manually programming irrigation and/or nutrient application are based on static models; while DSSs used for automatic control are based on dynamic models.

## 3. Models and DSSs for irrigation scheduling in vegetables

### 3.1. *General approaches to irrigation scheduling*

To assist with the determination of the timing and volumes of irrigation of vegetable crops, two main approaches are generally used, (a) the water balance method based on estimation of crop evapotranspiration (ETc), and (b) soil moisture or plant sensors. The use of sensors to assess plant water status for irrigation scheduling of vegetable crops has been investigated (Gallardo et al., 2006a, b; Fernández, 2014) but there has been very little implementation in commercial production. The use of soil moisture sensors for assisting with irrigation scheduling of vegetable crops was reviewed by Thompson and Gallardo (2003); Gallardo et al. (2013); De Pascale et al. (2017), and Incrocci et al. (2020). In the present article, the major focus will be on DSSs for irrigation scheduling (IS) of vegetable crops, based on the water balance method.

The water balance is a standard and well-established method for irrigation scheduling (IS) (Allen et al., 1998). It estimates irrigation volumes and informs when to irrigate (i.e. irrigation frequency). It is easy-to-use and generally has little cost. There is some uncertainty with its recommendations resulting from errors associated with the estimation of its various components. Using this approach, irrigation volumes are ETc minus effective rainfall, both since the previous irrigation; additional irrigation should be applied to consider irrigation application efficiency and the salinity of irrigation water (Rhoades and Loveday, 1990). To effectively use the water balance method, good estimates of ETc are an important requirement.

### 3.2. *Estimation of crop evapotranspiration*

The FAO56 approach (Allen et al., 1998) is the most established method to determine ETc. In this approach, ETc is estimated as the product of (a) reference evapotranspiration (ETo), derived from local climatic data, and (b) the crop coefficient (Kc), using general or locally-derived values (Allen et al., 1998). Reference evapotranspiration can be estimated using FAO recommended equations (e.g. FAO 56-Penman Monteith; Allen et al., 1998; ) or using other equations (Doorenbos and Pruitt, 1977) calibrated for specific conditions (e.g. Fernández et al., 2010). To determine Kc values, two approaches have been proposed by the FAO56 (Allen et al., 1998): (1) the single coefficient approach that considers soil evaporation and plant transpiration together in a single coefficient, and (2) the dual coefficient approach that separately calculates two coefficients, one for each of these two components of ETc. The dual approach is more accurate for daily estimation of ETc, and is recommended for frequently irrigated vegetable crops (Allen et al., 1998). In vegetable crops with slow initial growth rates, such as lettuce, Kc values are strongly influenced by soil evaporation. For these crops, models that separately calculate soil evaporation and plant transpiration are recommended (Cahn and Johnson, 2017). Several dual coefficient models have been developed for vegetable crops (Gallardo et al., 1996; Johnson et al., 2016; Mirás-Avalos et al., 2019).

In using the standard FAO56 methodology, for both the single and dual crop coefficient approaches, three constant Kc values are used, one for each of three different fixed length crop stages (Allen et al., 1998). The use of fixed Kc values for fixed length periods is not well suited to vegetable crops because of appreciable variation in planting dates and crop growing period in response to market prices, weather conditions, cropping cycles and farm management considerations. The effects of different cropping dates on Kc values are apparent in the very different seasonal evolution of measured Kc values for winter and spring planted greenhouse melon crops in Fig. 1.

Models have been developed to calculate Kc values to deal with the variability of vegetable cropping cycles. Kc is generally strongly related to crop growth (Grattan et al., 1998) which is strongly influenced by thermal time. Orgaz et al. (2005) developed two simple Kc models based on thermal time for greenhouse vegetable crops, one for pruned and the other for unpruned crops. Gallardo et al. (1996) developed a Kc model for open field lettuce that calculated transpiration from ground cover. Ground cover was estimated from ETo using an empirical model (Gallardo et al., 1996); ETo was available from a network of climate

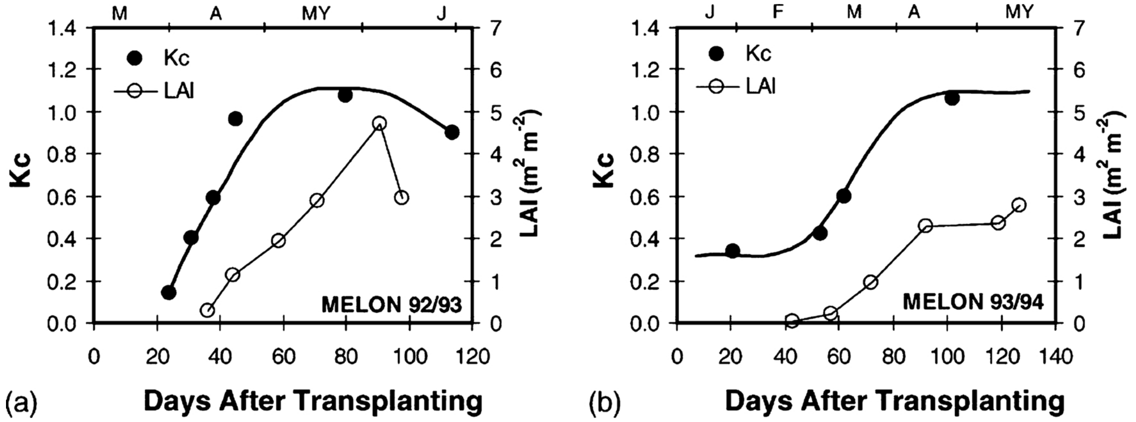

**Fig. 1.** Seasonal evolution of crop coefficient (Kc) and leaf area index (LAI) for no supported melon crops grown in a plastic greenhouse, (a) late planting on 8/3/93 and (b) early planting on 10/01/94. Reproduced with permission from Orgaz et al., 2005. Evapotranspiration of horticultural crops in an unheated plastic greenhouse. *Agricultural Water Management* 72, 81–96, published by Elselvier.

stations (CIMIS in California). In other studies, crop coefficient has been modelled using Leaf Area Index (LAI) measured *in-situ*, with a hand-held ceptometer, as an input (Baille et al., 1994). The requirement for measured LAI or measured crop cover data is a major practical limitation, as these require time-consuming measurements. A recent alternative is the use of remote sensing (aerial or satellite) to obtain normalized difference vegetation index (NDVI) values to estimate crop canopy cover (Courault et al., 2005; Neale et al., 2005) which in turn can be used to estimate Kc (Pardossi and Incrocci, 2011).

The ETo equations and Kc models, that enable calculation of ETc, require climate data. The type of climate data determines the nature of the estimation of ETc and any subsequent irrigation recommendations. ETc estimation and irrigation recommendations can be either (1) for the short-term future (e.g. in the next few days) based on anticipated climate data or (2) immediate, based on recent retrospective climatic data. Anticipated climate data is either historical climatic data (average of long term climatic data) or forecast climate data (e.g. Gavilán et al., 2015). Historical climate data can be used where climate conditions are particularly stable such as in Mediterranean greenhouses (Bonachela et al., 2006). The use of historical climate data has the advantage that an irrigation schedule for the whole crop can be prepared before the crop. Forecast climate data can be readily used for open field crops. In contrast, for greenhouse crops, there are challenges to model/estimate future climatic considerations inside an individual greenhouse from forecast data. An approach to use forecast climate data for greenhouses was developed by Gavilán et al. (2015). Immediate recommendations, for the day in question can be developed from recent retrospective climate data, collected on site or from a nearby climate station. This recent retrospective approach has been referred to as using “real time data” (Bonachela et al., 2006) because it uses measured data. Regional public services providing irrigation recommendations have been established, using this retrospective approach. Users select the nearest climate station from the local network; examples are the CIMIS network in California (http://www.cimis.water.ca.gov/), FAWN in Florida (https://fawn.ifas.ufl.edu/), Estaciones Agroclimáticas, of the Junta de Andalucía in Spain (https://www.juntadeandalucia.es/agriculturaypesca/ifapa/ria/servlet/FrontController). Alternatively, on-farm climate stations are an increasingly affordable option; users should be aware that they must be correctly sited and maintained.

Given the mathematically complexity of calculating (a) ETc which involves equations/models to calculate both ETo and Kc, and (b) the water balance, computer and spreadsheets programs have been developed since the 1980s to facilitate these calculations. These programs incorporate models required to estimate ETc, calculate the water balance, and estimate additional irrigation required to deal with irrigation application efficiency and the salinity of irrigation water.

The use of computer technology enables numerous and frequent calculations to be made, various inputs to be considered, access to online databases (e.g. climate or soil data), use of stored data records for a given field, and record keeping. By incorporating the models into DSSs (e.g. software or apps), the DSS outputs can be used to manually schedule irrigation or can be connected directly to irrigation controllers to automatically activate and stop irrigation. Additionally, sensors measuring soil water or crop water status can provide input data. Where considered appropriate, the use of soil moisture sensors in combination with the water balance method within a DSS could be useful to verify ETc and water balance calculations.

### 3.3. DSSs for managing irrigation in open-field vegetable crops

This section will consider DSSs that were developed for or include vegetable crops. The focus will be primarily on European DSSs. Therefore, most DSSs that have been developed specifically for other types of crops and that have been developed elsewhere will be overlooked. Some of those of notable relevance will be referred to.

Numerous DSSs for irrigation scheduling of field crops, including vegetables, have been developed by Extension services, Universities, Research Centers and other institutions/services involved in management of water resources, particularly in the USA. In the USA, numerous DSSs have been developed for individual states or regions, e.g. California and Washington State (Cahn and Johnson, 2017). Additionally, DSSs have been developed by smaller irrigation districts to provide a service to their member farmers (e.g. Montoro et al., 2011), and by private advisory companies for either international or local use (e.g. Hidrosoph at http://www.hidrosoph.com/EN/index.html; Wise Irrisystem at https://wiseagrotecnologia.com/). Many DSSs have been developed within individual publicly financed projects of limited funding and duration. Unfortunately, many of these DSSs have effectively disappeared within several years of being produced (“broken links in internet”) because of the lack of continuity in funding or motivation.

The capacities and technical sophistication of DSSs for irrigation scheduling has increased rapidly, in recent decades, in parallel with the development of ICT. The first DSSs in the 1980s and early 1990s were simple spreadsheets or stand-alone programs operated on personal computers. Several early spreadsheet DSSs developed for regional application in the USA calculated crop water requirements and irrigation frequency using the water balance (Cahn and Johnson, 2017). They required users to obtain ETo data from elsewhere and, manually enter it into the DSS; this requirements discouraged use of these DSSs in commercial farms.

One well known and established DSS for irrigation scheduling is

CROPWAT (Smith, 1992; http://www.fao.org/land-water/databases-and-software/cropwat/en/) developed by FAO to calculate crop water requirements of numerous crop species including vegetables, for different management conditions. CROPWAT is often used as an educational tool to teach the principles of irrigation scheduling, and for demonstration or planning purposes rather than as field tool for farmers. AQUACROP (Steduto et al., 2009) is a crop growth model, also developed by FAO, which simulates yield response to water supply. In addition to irrigation management, it can be used as an educational and benchmarking tool, and for scenario analysis for cereal and other field crops including vegetables (Li et al., 2018).

In Europe, a number of DSSs for irrigation scheduling of outdoor vegetable crops are available; some of which have appreciable numbers of users. In Italy, IRRINET (Mannini et al., 2013; Climate ADAPT, 2020) is a web service operated by the CER (a consortium of irrigation administrators) in the Emilia-Romagna region. IRRINET provides irrigation advice for crops of several vegetable species, using the water balance. It provides users with irrigation scheduling advice through a Web interface, SMS messages and a Tablet App. The Irrigation-Advisor DSS (Mirás-Avalos, 2019), which is based on weather forecasts and is able to separately determine soil evaporation and crop transpiration, has been recently developed for vegetable crops in the Mediterranean coast of Spain. It has been successfully evaluated in commercial farms. In Germany, the Gesenheim Irrigation Scheduling (GS) was developed for sprinkler irrigation management of about 27 vegetable crops in Central Europe (Olberz et al., 2018). This was initially developed as a spreadsheet program. A web-based version with smartphone App access called GSHEN is being finalized (as of April 2020). In the web-based version, Kc values are calculated from cumulative temperature, and ETo using the FAO56 Penman-Monteith equation with climate data input from the German weather service.

The most relevant DSSs for assisting with irrigation management of vegetable crops (open field and greenhouse) discussed in this article are presented in Table 1. Given the large number of DSSs available, the listed DSSs were selected using the criteria of (i) relatively recent DSSs that are currently in use or have high scientific relevance, (ii) DSSs with practical application, (iii) being innovative (iv) being used in Europe or are particularly relevant, and (v) detailed descriptions are available.

### 3.4. *DSSs for irrigation scheduling of greenhouse-grown vegetable crops*

Different types of models have been developed for irrigation management of greenhouse-grown vegetable crops. The type of model, complexity and characteristics vary according to the growing media (soil or soilless) and the level of technology of the greenhouse.

The required accuracy and time scale for estimation of ETc depends on the growing media. For soilless crops, a very high degree of accuracy and a small time scale (e.g. every minute) are required because irrigation is applied on a scale of hours/minutes, and substrates generally have very small retention of crop available water. In soilless crops, these models must dynamically respond to short-term changes in climate conditions. For soil-grown crops, given the irrigation intervals and greater holding capacity of soils, a relatively lower level of accuracy is acceptable.

Generally, with soilless crops, irrigation is automatic, and dynamic models are integrated with the irrigation controllers. Generally, these models calculate accumulated transpiration since the previous irrigation. Once the calculated accumulated volume of transpiration reaches a threshold value, irrigation is automatically initiated. The fixed irrigation volume considers additionally a drainage fraction to control root zone salinity. In soil grown crops, automatic irrigation is uncommon (at least currently in Mediterranean greenhouses). Current practice for soil grown crops (in Mediterranean greenhouses) is the use of static models using historical climate incorporated into DSSs to provide plans of irrigation that can be formulated when the crop is planted.

Models for greenhouses with heating have to consider night-time transpiration that can be an important component of ETc in some crops such as cucumber (de Graaf and van den Ende, 1981). Also, the use of screens (shading, thermal) can affect the accurate simulation of ETc (Thompson et al., 2015).

The models available for irrigation scheduling in greenhouses can be classified into three broad categories: (1) simple models based on radiation, (2) models based on the energy balance, and (3) models that adapt the standard FAO56 methodology (Allen et al., 1998), originally developed for outdoor crops, to greenhouse-grown crops. A common characteristic of these three categories of models is that crop water requirements are calculated as the product of two components: (1) a climate component that considers the effect of the atmosphere on crop water demand, and (2) a crop component that considers how the characteristics of the crop (size, morphology, leaf area etc.) modify the atmospheric demand for water. In some models, such as those based on the energy balance, these two components are combined in one equation, while in models based on the FAO56 approach, these two components are calculated separately.

Radiation models are based on the high correlation between ETc and solar radiation (Villèle de (1972)). Generally, the input data for these models are solar radiation outside the greenhouse and the transmissivity of the greenhouse roof. One of the first models to estimate ETc of greenhouse vegetable crops, was the radiation model developed by Villèle de (1972) for Dutch greenhouses. It calculates ETc from external solar radiation, roof transmissivity, crop coefficient values, and empirical coefficients. This model has been used with irrigation controllers. However, the model of Villèle was found to be inadequate for calculations of ETc for short periods as required for soilless crops, and where active climate control was used (Bakker, 1991). de Graaf and van den Ende (1981) subsequently developed a simple radiation-based crop model for Dutch greenhouses, with climate control, that calculates ETc from external solar radiation, the difference in temperature between the heating pipes and the greenhouse air, and the size of the plants. Currently, for soilless cropping in Dutch greenhouses, solar radiation equations such as de Graaf and van den Ende (1981) are used to steer irrigation management, but they are supplemented by the use of drainage fractions and weighing scales (W. Voogt, Wageningen University ad Research, The Netherlands). This is discussed in detail by van der Salm et al. (2020).

Energy balance models are theoretically the best models to calculate short term rates of ETc because of their high precision. However, they are relatively complex and require measures of (i) climatic parameters such as radiation and vapor pressure deficit (VPD), (ii) crop parameters, such as LAI, which are difficult to obtain, and (iii) foliar and aerodynamic conductance values. An example is the model of Baille et al. (1994) which is a simplification of the Penman-Monteith and has had appreciable use in research. However, it requires accurate estimation of LAI, which is a major limitation for practical use (Medrano and Alonso, 2007).

The FAO56 approach has been successfully applied to soil-grown crops in low to medium technology plastic greenhouses in the Mediterranean region, where irrigation is normally applied every 1–4 days. Various equations to estimate ETo in these conditions were evaluated by Fernández et al. (2010, 2011) and reviewed by Gallardo et al. (2013). Incrocci et al. (2020) describes in detail the use of the FAO 56 approach in greenhouses.

The PrHo DSS (Fernández et al., 2009) has been developed to calculate daily crop irrigation requirements for the major vegetable crops in Almeria, Spain, based on calculation of ETc as the product of ETo, estimated with the Almeria Radiation equation (Fernández et al., 2010), and Kc values, estimated by the models described by Orgaz et al. (2005). Historical daily climate data are used for the calculation of daily ETo and Kc values. Alternatively, real time climatic data can be used. A Windows version of this DSS in Spanish is freely available at Fundación Cajamar (2020). PrHo DSS considers the effect of whitewashing used for greenhouse cooling. Irrigation requirements consider

**Table 1**
Principal decision support systems (DSS) for assisting with irrigation management of vegetable crops in Europe. More information on each DSS is provided in the text. N.A.: information not available.

| Name of DSS | Main outputs | Mode operation | Climatic data acquisition | Species | Software available | Country/area for which developed or used | Reference |
|---|---|---|---|---|---|---|---|
| IRRINET | Irrigation frequency and volume, soil water dynamics, crop growth, ETc, water table, economic benefits | Web-GIS interface; Smartphone/Table App; SMS messages | Real time | Vegetable and orchard | https://www.irriframe.it/irriframe/home/Index | Six regions in Italy | Mannini et al. (2013) |
| ISS-ITAP | Weekly irrigation volume or time | Web, email or SMS on request | Real time | 35 crops: cereals, vegetable, fruit trees, others | http://www.itap.es/inicio/riegos/ | Castilla-La Mancha, Spain | Montoro et al. (2011) |
| Irrigation advisor (IA) | Soil evaporation and crop transpiration, daily water balance, irrigation volume, irrigation time | N.A. | Historical climate data; real time | Potato, lettuce, endive, muskmelon | N.A. | Southeast Spain | Mirás-Avalos et al. (2019) |
| IRRIX | Automatic irrigation scheduling (water balance and soil and plant sensors) | Web-based | Real time; forecast weather | Fruit trees, vegetable, | Available for research on demand | Catalonia, Spain | Casadesús et al. (2012) |
| GSEHEN<br>GS-Mobil<br>3) Gesenheim irrigation scheduling (GS) | Volume and date of irrigation | Web-based, Smartphone App<br>Web-based, Smartphone App<br>Downloadable spreadsheet | Real time, historical | 27 vegetable crops<br>Lettuce, onion<br>27 vegetable crops | Being finalized (February 2019).<br>App at https://helm-software.de/<br>Downloadable | Central Europe | Olberz et al. (2018) |
| PrHo | Volume and time of irrigation | Downloadable software | Historical climate data; real time | Main vegetable species grown greenhouses in SE Spain | https://www.cajamar.es/es/agroalimentario/innovacion/investigacion/documentos-y-programas/ | Greenhouses of SE Spain | Fernández et al. (2009) |
| Hydro-Tech | Automatic irrigation scheduling (water balance and soil sensors) | Web-based | Real time; forecast weather | peach and olive orchards, wine and table grapes, and vegetables. | Exploited by a company (www.blueleaf.it.) | Apulia Region (Italy) | Todorovic et al. (2016) |

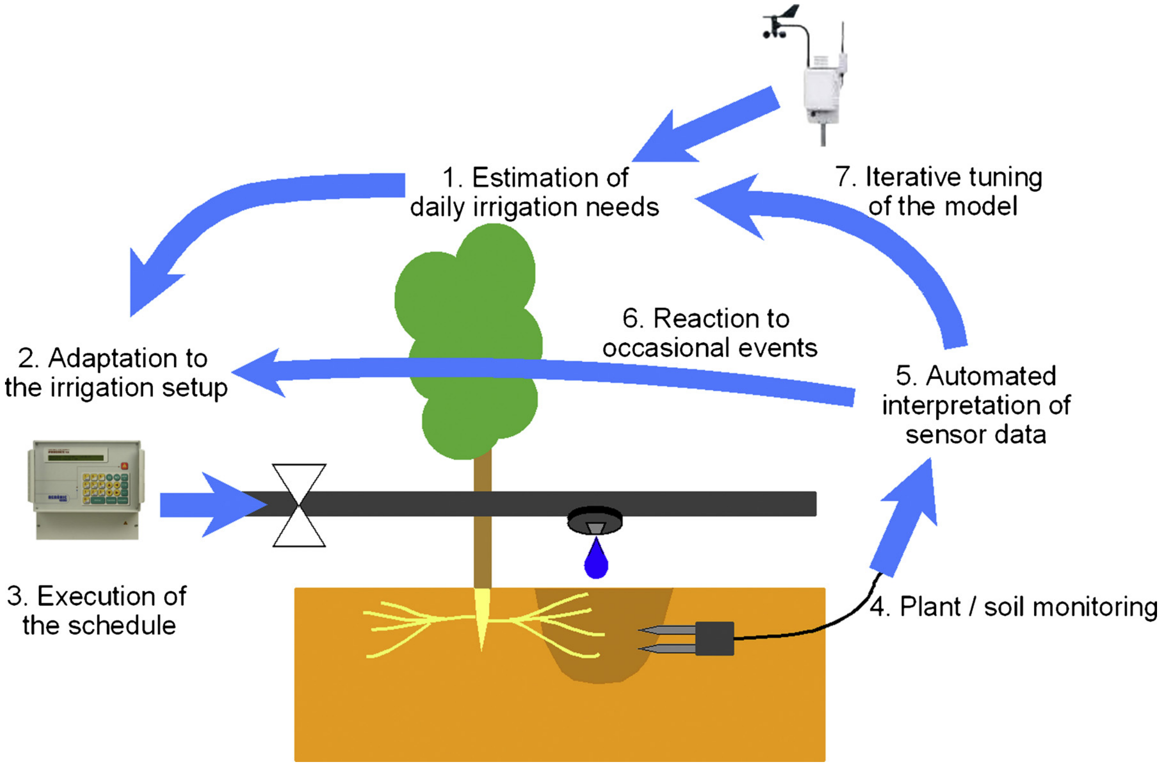

**Fig. 2.** Schematic diagram of the control scheme used in the IRRIX-DSS for automatic irrigation. The daily irrigation dose (DID) is determined, in mm $d^{-1}$, by a simple model (task 1) using weather and crop data. Then DID is translated to a schedule (task 2) attending to the singularities of each irrigation setup. The schedule is executed (task 3) and its effects on the crop water status are monitored by soil or plant sensors (task 4). Data acquired with sensors require elaborate interpretation (task 5) consisting on assessing the reliability of each sensor and calculating some daily indicators of the crop water status. Detection of some occasional event triggers a specific reaction (task 6). If not, the indicators of crop water status are used for tuning the model (task 7), closing the loop. Reproduced with permission from Casadesús et al., 2012. A general algorithm for automated scheduling of drip irrigation in tree crops. Computers and Electronics in Agriculture 83, 11-20, published by Elselvier.

irrigation water salinity and the application uniformity of irrigation. The VegSyst-DSS is another Windows operated DSS that calculates irrigation requirements for greenhouse-grown vegetable crops in south-east (SE) Spain, it is described in section 5.

### 3.5. Use of DSSs for irrigation scheduling in combination with soil and plant sensors

Model-based DSSs can be combined with soil and plant sensors to verify model calculations, and to adjust the calculations to consider current crop and soil conditions. The WATERBEE system (http://waterbee-da.iris.cat) “Smart Irrigation and Water Management system” recommends irrigation management based on crop modelling combined with soil water content measurements by sensors. The IRRIX DSS is a web application developed by IRTA in Catalonia, Spain (Casadesús et al., 2012) for automatic irrigation scheduling of fruit trees using a water balance to estimate the irrigation requirements and soil water sensors to correct the prediction of the model (“ground truth”) and to subsequently recalculate the schedule (Fig. 2). IRRIX DSS can operate autonomously throughout a cropping season (Casadesús et al., 2012). IRRIX DSS has been successfully adapted to greenhouse vegetable crops (M.D. Fernández, personal communication).

The Hydro-Tech (Todorovic et al., 2016) is a cloud-based application for automatic real-time irrigation scheduling based on the water balance. The FAO56 approach for the estimation of ETc using real time or forecast weather is combined with continuous soil water content monitoring and remote control of the water supply network. The Hydro-Tech system was tested in commercial farms resulting in 5–20 % reductions of applied water (Todorovic et al., 2016). Currently this system is promoted by the company Blueleaf (www.blueleaf.it).

### 3.6. Use of DSSs for irrigation scheduling in combination with remote sensing

Model-based DSSs can integrate remote sensing images to improve the estimation of crop parameters involved in the calculation of Kc values. The AQUATER software is a complex DSS based on a simulation model for irrigation scheduling of several species including tomato, in semi-arid Mediterranean areas (Acutis et al., 2010). Remote sensing images were used to improve the simulation of LAI and therefore of the calculation of ETc. Additionally, model-based DSSs can be integrated with a Geographical Information System (GIS) to apply the DSS on a large scale (Acutis et al., 2010). With the GIS, it is possible to map the data input and outputs and display soil, climate and crop data. The Spanish DSS, Irrigation-Advisor (Ramirez-Cuesta et al., 2018) has the capacity to use satellite images to determine the crop ground cover from measurements of a vegetation index (e.g. NDVI) and is implemented in a GIS system. In Australia, the IrriSAT (Car et al., 2012) is a weather-based irrigation management technology that uses remote sensing to provide site-specific crop water management recommendations across large spatial areas. FIGARO: “Flexible and Precision Irrigation Platform to Improve Farm Scale Water Productivity” (http://www.figaro-irrigation.net/outputs/the-figaro-platform/en/ ), is a precision agriculture DSS based on remote sensing, soil sensor measurements and the AQUACROP model that enables water and energy savings while maintaining or increasing production.

### 3.7. Adoption of DSSs for irrigation scheduling

A number of examples of widespread use by farmers of individual DSSs for irrigation scheduling demonstrates their potential for substantially improvement of irrigation management on a large scale. IRRINET is used on 16,000 farms (Mannini et al., 2013). Leib and Elliott, 2000 reported that WISE, a DSS for irrigation scheduling in Washington State provided recommendations for 120,000 ha of crops per year. CropManage (described in section 5; Cahn et al., 2014) has 1500 registered active farms on the Central Californian coast, and provided 1500–2300 monthly recommendations during the period February to September 2019 (M. Cahn, University of California – Davis, personal communication). While technically not a DSS, the ISS-ITAP centralized irrigation scheduling service uses a very similar approach to provide recommendations in Albacete, central Spain (Montoro et al., 2011). It is operated by a government agency and provides recommendations to growers by email and SMS. In 2005, it was being used on 33,500 ha, and its use was associated with an appreciable improvement in irrigation practice (Montoro et al., 2011). In all of these successful cases, a public or private service provided or provides ongoing technical support.

However, many DSSs produced for irrigation scheduling have had little use on commercial farms. The likelihood of adoption can be increased by considering dissemination, training and technical support, when developing the DSS (Hochman and Carberry, 2011). Developing technical and dissemination plans within a framework combining advisors, farmers, researchers and software engineers will enhance the possibilities of adoption (Hochman and Carberry, 2011). Activities to inform and train farmers and to provide support, particularly during the first months of use, are required to facilitate adoption by farmers. Barriers to adoption of DSSs for irrigation scheduling are limited interest of farmers to reduce water use, and the effort required relative to the perceived benefits. There appears to be a general reluctance of vegetable growers, particularly older growers to adopt new ICT-based approaches and to change their established procedures regarding decision making for irrigation and nutrient management.

In summary, barriers to the wider adoption by commercial vegetable growers of DSSs for irrigation scheduling techniques are: (i) the time required to use the programs, (ii) the practical difficulties associated with the use of software, (iii) the common lack of effective procedures to train and support growers, (iv) the lack of on-going technical support, and (v) that growers are reluctant to take what they perceive as a risk with high value crops that are sensitive to crop water stress (Gallardo et al., 2013; Cahn and Johnson, 2017).

## 4. Models and DSSs to optimize nutrient management

This section will deal mostly with N because of its agronomic and environmental importance. Where other nutrients are dealt with by particular DSSs/model, they will be specifically referred to. There are two major general approaches with which simulation models and DSSs are used to assist with crop nutrient management, namely: (1) calculation of fertilizer requirements for individual crops (Thompson et al., 2017), and (2) for scenario analysis to demonstrate the effects of different nutrient management practices on crop response and nutrient losses. A third emerging approach is of DSSs to interpret crop or soil monitoring measurements (e.g. proximal sensors, soil analyses, sap analyses (Incrocci et al., 2017; Thompson et al., 2017; Padilla et al. (2020)).

As with irrigation management, DDSs to assist with nutrient management of diverse crops have available since the late 1980s as modified spread sheets or stand-alone computer programs, both operated on personal computers (Thompson et al., 1997). A listing of the principal DSSs for assisting with nutrient management of vegetable crops, reviewed in this article, is presented in Table 2.

### 4.1. General considerations

Generally, practical DSSs for the calculation of crop and site specific fertilizer requirements for individual crops contain relatively simple simulation models with few inputs. The information required for those inputs is generally readily available to growers and advisors. Such DSSs have relatively few parameters that require calibration for a particular combination of species, site and cropping system. Examples of practical DSSs with these characteristics are CropManage (Cahn et al., 2014) and VegSyst-DSS (Gallardo et al., 2014). Models used for scenario analysis are generally appreciably more complex with more inputs and parameters e.g. EU-Rotate_N (Rahn et al., 2010). Scenario analysis models are very useful for demonstration purposes, but are too complex for practical crop management. Generally, both practical and scenario analysis DSSs use daily time steps.

For the determination of crop N requirements, models and DSSs generally calculate N balances (Thompson et al., 2017; Tei et al., this issue), and estimate many of the components of the N balance, e.g. crop N uptake, mineralized N, N losses. Some N budget components e.g. N mineralization rates and N losses may be estimated using simple factors, relatively simple equations or models. Total loss can be estimated based on the efficiency of N use (e.g. in VegSyst-DSS). The N efficiency term is the percentage of N sources that is recovered by the crop (Thompson et al., 2017). In more complex models, the different N loss processes are individually simulated with sub-models that require numerous inputs. However, estimating individual N loss pathways is complex, and composite N loss terms or N efficiency factors are commonly used. Doing so appreciably reduces the number of DSS/model inputs. A general N efficiency factor can be applied to all N sources, or individual N efficiency factors can be applied to each N source considered by the DSSs/model (Thompson et al., 2017).

To model crop N uptake, the most commonly used approach is to simulate both crop dry matter production and the N content of the crop; the product of the two being the crop N uptake. Crop N content is often estimated using N dilution curves (Greenwood et al., 1990). The N dilution curves may be for (a) the critical N content (CNC) versus dry matter production, CNC is the minimum crop N content at which dry matter production is not N limited (Greenwood et al., 1990), or (b) crop N content of a well fertilized crop where some luxury N uptake occurs. Other approaches to calculate crop N uptake have been based on expected yield, which is an input parameter, or more mechanistic models that consider N uptake by roots (Incrocci et al., 2017).

Different levels of mathematical complexity have been used in these models and DSSs. The more complex models (e.g. EU-Rotate_N (Rahn et al., 2010)), simulate numerous crop and soil processes such as dry matter production, crop N uptake, yield, ETc, root growth and distribution, root N uptake and various components of the soil N and water dynamics and specific N losses. GesCoN is another DSS where root growth is modelled and N soil dynamics are simulated (Elia and Conversa, 2015; Elia et al., 2020a, b. In contrast, more practical models and DSSs such as the VegSyst-DSS (Gallardo et al., 2014) simulate a small number of processes related to crop growth, N uptake and ETc. This avoids the complexity associated with modelling root growth, soil water dynamics, soil N transformations and N losses. The alternatives to modelling numerous processes are the use of relatively simplified equations, fixed coefficients such as N efficiency terms, and a strong focus on the most relevant processes related to N use and demand. The more complex models/DSSs that simulate soil N dynamics, commonly have components that simulate ETc and soil water dynamics, because soil N and water dynamics are closely linked.

### 4.2. Models and DSSs for practical nutrient management

Several DSSs based on simulation models have been developed in Europe to assist with N fertilization of vegetable crops e.g. N-Expert (Fink and Scharpf, 1993; Feller et al., 2011), Azofert® (Parneaudeau et al., 2009; Machet et al., 2017), VegSyst-DSS (Gallardo et al., 2011, 2016) and GeCoN (Elia and Conversa, 2015). Common to these DSSs is the overall objective of using mineral N fertilizer as a supplement to soil N sources (e.g. soil organic matter, crop residues, manure), and that the

**Table 2**
Principal decision support system (DSS) for assisting with nutrient management of vegetable crops. More information on each DSS is provided in the text. N.A.: information not available.

| Name of DSS | Main outputs | Mode operation | Climatic data acquisition | Species | Software available | Country/ area for which developed or used | Reference |
|---|---|---|---|---|---|---|---|
| N-Expert 4 | N, P, K and Mg fertilizer recommendations | Downloadable software | Not clear from available description | Field vegetable crops | http://www.igzev.de/n-expert/?lang = en | Germany | Feller (2015) |
| Azofert | N fertilizer rate for different yield objectives, timing to apply the fertilizer | Used by advisory services | Not clear from available description | 40 annual crops (cereals, industrial and vegetable crops | Used by advisory services | France | Machet et al. (2017) |
| PLANET | N, P and K fertilizer recommendations; Field and farm nutrient balances, record keeping | Downloadable software | N.A. | Numerous vegetable and cereal crops | http://www.planet4farmers.co.uk/Content.aspx?name=Home | England, Wales and Scotland | http://www.planet4farmers.co.uk/Content.aspx?name = PLANET<br>Thompson et al. (2017) |
| RB209 | N, P and K fertilizer recommendations | Smart phone App | N.A. | Numerous vegetable and cereal crops | Apps (iOS; Android) at: https://ahdb.org.uk/nutrient-management-guide-rb209 | England and Wales | https://ahdb.org.uk/nutrient-management-guide-rb209<br>Thompson et al. (2017) |
| EU-Rotate_N | Crop N uptake, components of N balance (also ETc, soil water balance) | Downloadable software | Past climate; historical climatic data | 70 vegetable and field crops | https://warwick.ac.uk/fac/sci/lifesci/wcc/research/nutrition/eurotaten/ | Europe | Rahn et al. (2010) |

supplemental amount of mineral N fertilizer is sufficient to ensure maximum production while minimizing N loss.

The French Azofert® system is used to provide N recommendations for numerous vegetable crops and cereals (Parneaudeau et al., 2009; Machet et al., 2017). It has been adapted to various regions of France, Belgium and Switzerland (Maltas et al., 2015; Machet et al., 2017). Azofert® uses a N balance approach to prepare a N fertilizer recommendation. Crop N uptake is based on expected yield and standard crop N content values. Most of the N balance terms are modelled, such as N mineralization from various sources, and the N loss terms of immobilization, $NO_3^-$ leaching and ammonia ($NH_3$) volatilization. Soil mineral N at the beginning of the crop can be measured (Machet et al., 2017). Azofert® is a Windows program that operates in stand-alone mode or as a web-based program. It has been designed to integrate with data management systems used by French agricultural laboratories (Machet et al., 2017). Azofert® facilitates user-friendliness through a reduced number of inputs and a practical focus.

The German N-Expert is a Windows based program used to provide N recommendations for numerous vegetable crops and cereals (Fink and Scharpf, 1993; Feller, 2015). N-Expert also assists growers and fertilizer advisers to calculate P, K and Mg fertilizer requirement of vegetable crops and to prepare nutrient balances for N, P, K and Mg. The N fertilizer recommendations and the nutrient balances are required by German Law. The N recommendations are based on the KNS system (Thompson et al., 2017). N-Expert contains an updated database of nutrient uptake for all relevant field vegetable crops and for numerous other crops that are grown in crop rotations with vegetables. The N-Expert software and associated information are available in English and German and can be freely downloaded at: http://www.igzev.de/n-expert/?lang=en. 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 CAL-FERT software (Incrocci et al., 2013) is a DSS that calculates fertilization plans for N, P and K for various vegetable species, in Tuscany, Italy, by considering soil analysis, crop nutrient uptake and the mineralization of nutrients from soil organic matter and decomposition of biomass of previous crop residues. It is available in Italian at http://www.cespevi.it/softunipi/calfert.html. The CAL-FERT software is a static model that works with a target yield value, provided by the user, and a database 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 fertilizer requirements. Users can also input real time or forecast climate data.

In England and Wales, the RB209 fertilizer Manual provides fertilizer recommendations for vegetable and cereal crops (Thompson et al., 2017). Traditionally, the RB209 Manual was freely available as a booklet and more recently as a PDF file. Now, it can be downloaded as iOS and Android smartphone Apps, in addition to a PDF file (https://ahdb.org.uk/nutrient-management-guide-rb209). The RB209 Fertiliser Manual provides crop and field specific N, P and K fertilizer recommendations based on the crop to be grown, the residues from the previous crop, soil texture and winter rainfall.

PLANET (Planning Land Applications of Nutrients for Efficiency and the environment, (http://www.planet4farmers.co.uk/Content.aspx?name=Home) is a nutrient management Windows-based DSSs developed for use by farmers and advisers in England, Wales and Scotland. It provides N, P and K recommendations for cereal and vegetable crops. PLANET incorporates computerized versions of both the RB209 Fertiliser Manual for England and Wales (see Thompson et al., 2017; and Scotland's Rural College (SRUC) technical notes (http://www.sruc.ac.uk/downloads/120,451/crop_technical_notes). Part of it is essentially a database that contains and integrates the numerous fertilizer recommendation tables of the RB209 Fertiliser Manual, and the relevant Scottish recommendations. Additionally, it enables detailed record keeping of individual fields (crop history, soil analyses, manure applications, field size etc.) and can be updated during the cropping season. Nutrient balances can be calculated. The PLANET DSS is currently (February 2020) being reviewed by the British government. A number of commercial alternatives are available including GateKeeper https://farmplan.co.uk/crops/gatekeeper-grower/ and Muddy Boots http://en.muddyboots.com/. These commercial software programs incorporate the RB209 Fertiliser Manual through an application programming interface (API) (https://rb209-api-v1.ahdb.org.uk/). Therefore, the information of the RB209 Manual is used, but it is displayed through interface of the host software.

FertiliCalc (Villalobos et al., 2020) is a recently developed, very comprehensive, stand-alone Windows program that calculates N, P and K requirements for 149 crops, including many vegetable crops, in diverse environments. It is available in 29 languages, and can be downloaded at http://www.uco.es/fitotecnia/fertilicalc.html. Nitrogen recommendations are based on the expected yield and consideration of soil N supply.

A DSS that calculates N fertilizer recommendations for leafy vegetables has been 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 while avoiding an excessive N supply. The N fertilizer recommendations, that are subsequently calculated, are the amounts required to maintain the optimal soil mineral N content in the root zone. 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).

Several DSSs that calculate both crop N and irrigation requirements for fertigated vegetable crops have been developed, and are reviewed in section 5. These DSSs include GesCoN (Elia and Conversa, 2015) and VegSyst-DSS (Gallardo et al., 2014, 2016) in Europe and CropManage (Cahn et al., 2014) from California.

### 4.3. Models and DSSs for scenarios analysis of nutrient management

Many of the simulation models developed to evaluate the effects of crop nutrient management on production and nutrient loss to the environment are complex scientific models. Their use has generally been restricted to scientific studies, where they are used to aggregate 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 such as EPIC (Williams et al., 1984), STICS (Brisson et al., 2003), CropSyst (Stöckle et al., 2003), and the DSSAT group of models (Jones et al., 2003). These models are large and complex, with numerous inputs. They were generally developed for cereal crops; there have been a small number of adaptations to simulate N dynamics in vegetable crops (e.g. Cavero et al., 1998; Rinaldi et al., 2007; Onofri et al., 2009). While they may have appreciable scientific value, their practical use value for N management of commercial vegetable crops is limited.

The comprehensive EU-Rotate_N model (Rahn et al., 2010) was developed to assist with optimal N management of a wide range of vegetable and field crops throughout Europe (Rahn et al., 2010). For many vegetable species, EU-Rotate_N simulates crop growth and marketable yield, crop N uptake and ETc, and performs economic analyses. It models N mineralization from various sources, considers soil mineral N, and models various N loss processes. EU-Rotate_N has been used to simulate growth, production, and N and water dynamics in diverse European vegetable production systems e.g. cool season species in open field conditions in Germany (Nendel, 2009), open field vegetable crops in Mediterranean conditions (Doltra and Muñoz, 2010) and greenhouse-grown vegetables in SE Spain (Soto et al., 2014, 2018). By comparing scenarios, EU-Rotate_N can also be used to identify optimal

N management.

Suárez-Rey et al. (2016), calibrated and validated EU-Rotate_N with open field drip irrigated lettuce and escarole, and used it in combination with the KNS system (Thompson et al., 2017) to optimize N management of lettuce. Combined use of EU-Rotate_N and the KNS system suggested that the N fertilizer could be reduced by 57 % compared with local grower practice, while maintaining yield (Suárez-Rey et al., 2016). Additionally, simulations suggested that $NO_3^-$ leaching and residual soil mineral N would be considerably reduced (Suárez-Rey et al., 2016). This study demonstrated how EU-Rotate_N can be used to identify and demonstrate optimal N fertilizer recommendations.

CropSyst is an established suite of programs that can analyze production and environmental management at different temporal and spatial scales (Stockle et al., 2003). Most studies have been conducted with cereals; there has been little work with vegetable crops. Two exceptions have been Giménez et al. (2016) with garlic, and Suárez-Rey et al. (2016) with leafy vegetables. Giménez et al. (2016) evaluated N fertilization strategies with a garlic crop in southern Spain. Suárez-Rey et al. (2016) reported that the inability of CropSyst to consider drip irrigation and fertigation was a major limitation for using it with vegetable crops.

### 4.4. DSSs to assist with interpretation of monitoring data

The GREEN-FERT DSS (Incrocci et al., 2017) was developed at the University of Pisa, to assist growers using the Dutch 1:2 vol soil-water extract method (Sonneveld et al., 1990; Sonneveld and Voogt, 2009; Padilla et al. (2020)) for different vegetable species grown in soil in greenhouses in Italy. 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 (see Padilla et al. (2020)); users can modify the database according to their personal experience.

It is anticipated that with increasing use of different monitoring techniques to assist in N fertilization (Padilla et al. (2020)) that more DSSs to assist with interpretation of these data will be produced in the near to intermediate future.

### 4.5. Adoption of DSSs for nutrient management

It is difficult to measure the use of DSSs for nutrient management in commercial farming. Nevertheless, it is clear that programs such as Azofert ®, N-Expert, CropManage and GesCoN are being used to provide nutrient recommendations for numerous commercial farms. In the United Kingdom, PLANET has been used by many commercial farmers and advisors, and there have been thousands of downloads of the smartphone versions of the RB209 Fertiliser Manual since its release in 2017.

## 5. Models and DSSs for combined irrigation and nutrient management

Given that fertigation is being increasingly used with vegetable production, a number of recent simulation models and DSSs consider both nutrients (mostly N) and irrigation. In the form of practical DSSs, they provide crop specific recommendations for irrigation and N fertilizer. The comprehensive, scenario analysis models such as EU-Rotate_N (see section 4.3) simulate both N and water dynamics in the crop-soil system. However, these models are not suitable as practical crop management tools, and have been described in some detail in section 4.3. The models/DSSs to be considered here are Veg-Syst-DSS, GesCoN and Fertirrigere from Europe and CropManage from California (Table 3).

The VegSyst-DSS, based on the VegSyst simulation model, calculates daily irrigation and N fertilizer requirements, and nutrient solution N concentrations [N] for fertigated vegetable crops grown in greenhouses

**Table 3**
Principal decision support system (DSS) for assisting with combined irrigation and nutrient management of fertigated vegetable crops. More information on each DSS is provided in the text. N.A.: information not available.

| Name of DSS | Main outputs | Mode operation | Climatic data acquisition | Species | Software available | Country/area for which developed or used | Reference |
|---|---|---|---|---|---|---|---|
| VegSyst | Daily irrigation, N fertilizer rate, [N] of nutrient solution, N uptake concentration | Downloadable software | Historical climatic data | Seven vegetable species grown in greenhouses in SE Spain | https://w3.ual.es/GruposInv/nitrogeno/VegSyst-DSS.shtml | Greenhouses of SE Spain | Gallardo et al. (2014); (2016) |
| Ecofert/ GesCoN | Irrigation volume<br>N rate<br>N fertilizer types | Web-based; SmartPhone App | Real time, weather forecast, historical climate data | Open field processing tomato | http://www.ecofert.it (platform which manage the service) Ecofert (android App for smatphone) (Italian; English) | Italy, USA (FL) | Elia and Conversa (2015) |
| FERTIRRIGERE V2.11 | Daily irrigation and macronutrient requirements for fertigation and drip irrigation | MS-Excel platform | Real time, historical data | Open field processing tomatoes | N.A. | Italy | Battilani (2006) |
| CROPMANAGE | Soil evaporation and crop transpiration; irrigation frequency and volume, N recommendations | Web-based | Real time climatic data from CIMIS system (climate network in California) | Cool season vegetables (lettuce, broccoli, cabbage, cauliflower, and spinach) | https://cropmanage.ucanr.edu/ | Salinas Valley, CA, USA | Cahn et al. (2014) |

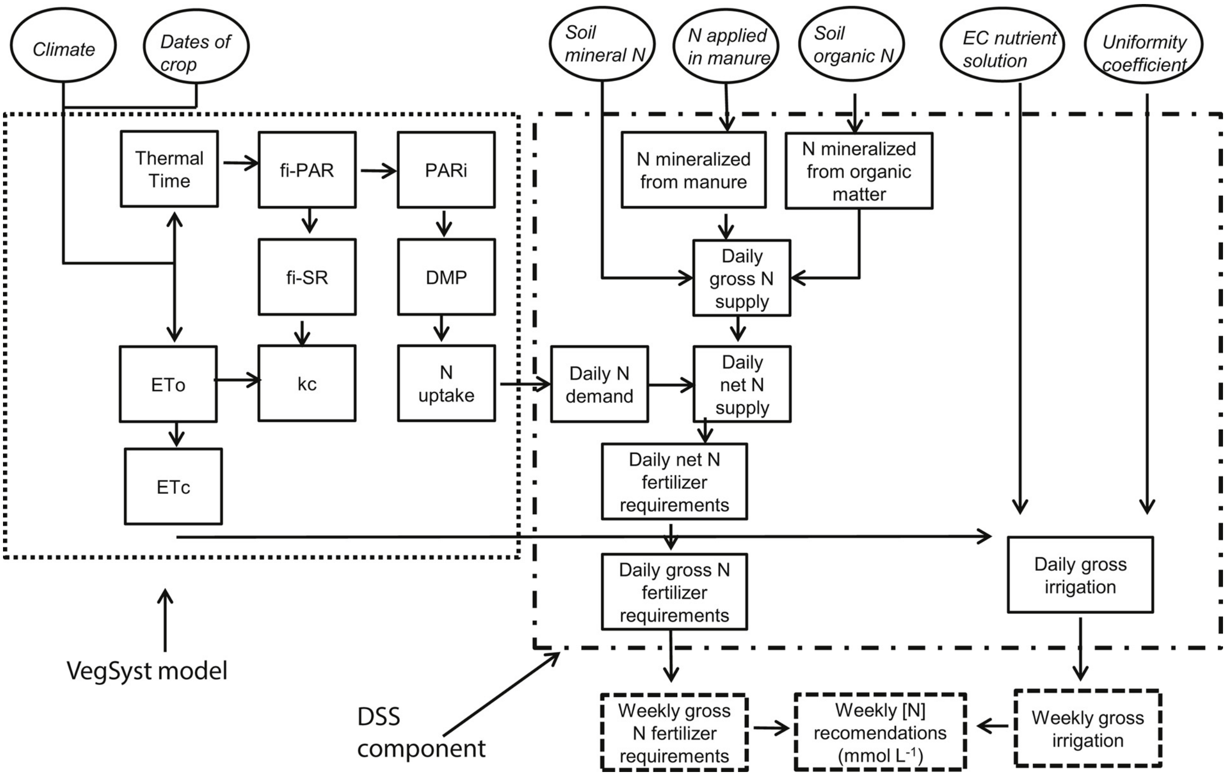

**Fig. 3.** Schematic representation of the VegSyst-DSS decision support system showing the calculations made by (1) the VegSyst simulation model component and (2) the DSS component. The simulations made by VegSyst model are enclosed in the *box* formed by the *dotted line*. The calculations made by the DSS component are enclosed in the *box* formed by the *broken* and *dotted line*. Parameters within *ovals* at the *top* are inputs. Parameters enclosed in *solid rectangles*, within the two *boxes*, are intermediate calculations. Parameters enclosed in *rectangles* formed by *broken lines*, at the *bottom*, are the outputs of the VegSyst-DSS. Reproduced with permission from Gallardo et al., 2014. Prototype decision support system based on the VegSyst simulation model to calculate crop N and water requirements for tomato under plastic cover. *Irrigation Science*, 32, 237–253, published by Springer-Verlag.

in SE Spain (Gallardo et al., 2014, 2016). The VegSyst simulation model, which is the core of VegSyst-DSS, is relatively simple; it calculates daily values of crop biomass production, crop N uptake and crop evapotranspiration (ETc) (Gallardo et al., 2011, 2016). It has been calibrated and validated for the major vegetable crops grown in greenhouses in SE Spain (tomato, sweet pepper, muskmelon, cucumber, zucchini, egg-plant, watermelon) (Gallardo et al., 2011, 2014; 2016; Giménez et al., 2013). It is assumed that there are no water or N limitations on crop growth. A detailed schematic representation of the VegSyst-DSS, showing the calculations of the VegSyst simulation model component and the DSS component, is presented in Fig. 3.

The VegSyst model component (Gallardo et al., 2011, 2016) simulates crop N uptake, and ETc as the product of ETo and Kc (Fig. 3). ETo is calculated using either the FAO56 Penman-Monteith adapted to Mediterranean greenhouses or the Almeria radiation equation (Fernández et al., 2010, 2011). Kc is calculated from solar radiation intercepted by the canopy (Gallardo et al., 2016; Fig. 3). The DSS component of VegSyst-DSS (Gallardo et al., 2014) then calculates daily crop N requirements from a daily N balance considering modelled crop N uptake, measured soil mineral N, estimates of N mineralised from manure application and soil organic matter, and the efficiency with which N from each N source is used (Gallardo et al., 2014, Fig. 3). The DSS component calculates crop water requirements by applying factors that consider irrigation water salinity and irrigation application efficiency to ETc (Gallardo et al., 2014, Fig. 3). VegSyst-DSS then calculates the [N] of the applied nutrient solution by dividing crop N requirements by irrigation requirements (Fig. 3). In Mediterranean greenhouses, long term average climate data can be used with acceptable accuracy (Bonachela et al., 2006). Using such data, at the beginning of a crop, VegSyst-DSS can prepare a plan of daily recommended irrigation volume and 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 Windows version of VegSyst DSS, in either English or Spanish, and an explanatory manual are available at http://www.ual.es/GruposInv/nitrogeno/VegSyst-DSS.shtml. The VegSyst model has been adapted to open field vegetable crops such as lettuce, spinach and processing tomato (Giménez et al., 2019), and a DSS for these crops is currently being developed. VegSyst-DSS was used as part of a prescriptive-corrective management package (Granados et al., 2013; Thompson et al., 2017) which appreciably reduced N fertilizer use and substantially reduced $NO_3^-$ leaching from a greenhouse pepper crop, compared to conventional local management (Magán et al., 2019).

The GesCoN DSS has been recently developed at the University of Foggia (Italy) to help improve N management of fertigated, open field vegetable crops (Elia and Conversa, 2015). Currently, it has been calibrated for open-field tomato (Conversa et al., 2015). It uses the water balance method to estimate crop water requirements with the daily calculation of the volume of wet soil explored by roots, and of water movement between the soil layers (Elia and Conversa, 2015; Elia et al., 2020a, b). ETc is estimated as the product of ETo and Kc values. The choice of ETo equations from FAO 56 Penman-Monteith, Priestley-Taylor, and Hargreaves-Samani is influenced by availability of climate data. The dual Kc approach is used. Crop N requirements are estimated using a daily N balance, with the daily calculation of crop N uptake (on the basis of dry weight accumulation and the specific N critical curve), N mineralization, and N movement between soil layers. The DSS provides daily recommendations of irrigation and N fertilizer requirements. Real time, historical or forecast climate data can be used.

The GesCoN DSS has been incorporated into the Ecofert platform to enhance access and its practical use. User access is through a web-application (www.ecofert.it) and an Android App (Ecofert). The DSS works with real-time and historical data through the Ecofert platform; the DSS can be connected with climate stations using the RESTful API method, removing the requirement for manual entry of climate data. When using automatic climate data entry, the only inputs required are those that initially describe the site, soil, crop (planting date, spacing), and irrigation system. During the crop cycle, using the Android App, the user is only required to update data on irrigations applied (as duration) and N applied. Testing on commercial farms showed that GesCoN reduced water and N use, and enabled appreciable financial savings (Elia et al., 2020a, b; Antonio Elia, University of Foggia, personal communication). The DSS has also been adapted to conditions in Philadelphia, USA.

FERTIRRIGERE V2.11 (Battilani (2006)) is a DSS based on a dynamic model that simulates water and macronutrient balances in the root zone, and provides recommendations of daily irrigation and macronutrient requirements for optimal fertigation management of drip irrigated open field processing tomatoes. When compared with grower management in 56 different farms in Tuscany (Italy), FERTIRRIGERE reduced the N application by 46 % on average, with no notable effects on fruit production and quality (A. Pardossi, University of Pisa, personal communication).

CropManage is a web-based DSS for irrigation and nutrient management developed for cool season vegetables in California (Cahn et al., 2014; https://cropmanage.ucanr.edu). The vegetable crops currently supported include lettuce, broccoli, cabbage, cauliflower, spinach, processing tomato and bell pepper. The irrigation scheduling algorithm uses real-time reference evapotranspiration data from the Californian CIMIS climate station network (http://cimis.water.ca.gov/). It uses a dual crop coefficient approach, described by Johnson et al. (2016) and Smith et al. (2016). Crop coefficients are calculated using an empirical model of canopy cover. The empirical models of fractional cover included for each vegetable crop, allows users to customize Kc curves for a specific season, bed width, and planting configuration. The estimation of irrigation intervals and volumes considers the soil water holding characteristics of the root zone.

Nitrogen management with CropManage is based on adding sufficient N in periodic (e.g. weekly) applications to maintain root zone soil mineral N close to a minimum optimal soil threshold for each species (Cahn and Johnson, 2017). The N fertilizer algorithm generates recommendations based on crop N uptake, current soil $NO_3^-$ status, and estimated soil N mineralization. In on-farm experimental trials, the use of this software reduced N fertilizer inputs by 30 % with respect to the fertilizer practice of growers (Cahn and Johnson, 2017). This DSS is supported by the University of California Cooperative Extension service; periodically “hands-on” workshops are organised to teach growers how to use the DSS and to encourage its adoption.

## 6. Conclusions

The complexity of decision making in modern, intensive, vegetable production requires the combined assessment of numerous factors and considerations, in the unique context of an individual vegetable crop. DSSs, commonly incorporating simulation models, can assist vegetable growers to make these site and crop specific decisions. Numerous DSSs have been developed in recent decades to assist with improving irrigation and nutrient management of vegetable crops. The technical sophistication of these DSSs has rapidly evolved with the rapid development of ICT from simple spreadsheets, requiring appreciable manual data entry, to smart phone Apps that access web-based programs that can automatically obtain climate and other data from various on-line data bases. A feature of the evolving technical sophistication is an appreciable increase in their user-friendliness and attractiveness to users. While there have been some success stories, numerous DSSs have had little on-going adoption as practical tools. Reasons for this include the complexity of earlier computer-operated spread sheets and programs, large manual data entry requirements, limited on-going funding to maintain the DSSs, and insufficient training and technical support for users. The previously-mentioned recent developments in ICT combined with Internet of Things technologies appreciably facilitate the use of DSSs. Additionally, the capacity to use forecast climate data enables accurate forward planning for the next week or so. With the current general emphasis on the digitalization of modern agriculture, there is currently considerable interest in the use of DSSs to assist with irrigation and nutrient management. Smartphone Apps provide a means whereby growers will have immediate access to DSS generated information, and in a form that they accustomed to dealing with. However, any DSSs, in whatever format must be based on sound agronomic science; any incorporated simulation models should be properly calibrated and validated for the conditions of use. Considerable care should be taken to ensure that they are easy to use and attractive to would be users, that the outputs are readily usable, that the DSS will be maintained for numerous years, and that training and technical support will be continually available to assist users.

## references

Ramírez-Cuesta et al. (2018) and Tei et al. (2020)

## Declaration of Competing Interest

The authors declare that there are no conflicts of interest associated with this manuscript.

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## References

Acutis, M., Perego, A., Bernardoni, E., Rinaldi, M., 2010. AQUATERS software as a DSS for irrigation management in semi-arid Mediterranean areas. Ital. J. Agron. 5, 205–215. https://doi.org/10.4081/ija.2010.205.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop Evapotranspiration. Guidelines for Computing Crop Water Requirements, Irrigation and Drainage Paper No. 56. FAO, Rome, Italy. https://doi.org/10.1016/j.eja.2010.12.001.

Anonymous, 1991. Council directive 91/676/EEC concerning the protection of waters against pollution caused by nitrates from agricultural sources. Off. J. Eur. Communities L135, 1–8.

Armbruster, M., Laun, N., Heger, A., Wiesler, F., 2013. Integrated nitrogen management – a strategy to improve nitrogen efficiency in intensive field vegetable production. In: D'Haene, K., Vandecasteele, B., De Vis, R., Crapé, S., Callens, D., Mechant, E., Hofman, G., De Neve, S. (Eds.), Proceedings of the NUTRIHORT, Nutrient Management Innovative Techniques and Nutrient Legislation in Intensive Horticulture for an Improved Water Quality Conference. Ghent, Belgium, 16-18 September. pp. 149–155.

Baille, M., Baille, A., Laury, J.C., 1994. A simplified model for predicting evapotranspiration rate of nine ornamental species vs. Climate factors and leaf area. Sci. Hortic. 59, 217–232.

Bakker, J.C., 1991. Leaf conductance of four glasshouse vegetable crops as affected by air humidity. Agric. For. Meteorol. 55, 23–36. https://doi.org/10.1016/0168-1923(91)90020-Q.

Battilani, A., 2006. Fertirrigere V2.11: a multi-target DSS to manage water and nutrient supply at macrozone Level. Acta. Hort. 724, 111–118. https://doi.org/10.17660/ActaHortic.2006.724.13.

Bonachela, S., González, A.M., Fernández, M.D., 2006. Irrigation scheduling of plastic greenhouse vegetable crops based on historical weather data. Irrig. Sci. 25, 53–62. https://doi.org/10.1007/s00271-006-0034-z.

Brisson, N., Gary, C., Justes, E., Roche, R., Mary, B., Ripoche, D., Zimmer, D., Sierra, J., Bertuzzi, P., Burger, P., Bussière, F., Cabidoche, Y.M., Cellier, P., Debaeke, P., Gaudillère, J.P., Hénault, C., Maraux, F., Seguin, B., Sinoquet, H., 2003. An overview of the crop model STICS. Eur. J. Agron. 18 (3), 309–332. https://doi.org/10.1016/S1161-0301(02)00110-7.

Cahn, M., Johnson, L., 2017. New approaches to irrigation scheduling of vegetables. Horticulturae 3, 1–20. https://doi.org/10.3390/horticulturae3020028.

Cahn, M., Smith, R., Farrara, B., Hartz, T., Johnson, L., Melton, F., Post, K., 2014.

Irrigation and nitrogen management decision support tool for vegetables and berries. In: Proceedings of the U.S Committee on Irrigation and Drainage Conference: Groundwater Issues and Water Management—Strategies Addressing the Challenges of Sustainability USCID. Sacramento, CA, USA. pp. 53–64.

Car, N.J., Christen, E.W., Hornbuckle, J.W., Moore, G.A., 2012. Using a mobile phone Short Messaging Service (SMS) for irrigation scheduling in Australia-Farmer´s participation and utility evaluation. Comput. Electron. Agric. 84, 132–143. https://doi.org/10.1016/j.compag.2012.03.003.

Casadesús, J., Màta, M., Marsal, J., Girona, J., 2012. A general algorithm for automated scheduling of drip irrigation in tree crops. Comput. Electron. Agric. 83, 11–20. https://doi.org/10.1016/j.compag.2012.01.005.

Cavero, J., Plant, R.E., Shennan, C., Williams, J.R., Kiniry, J.R., Benson, V.W., 1998. Application of Epic model to nitrogen cycling in irrigated processing tomatoes under different management systems. J. Agric. Food Syst. Community Dev. 56, 391–414.

Climate ADAPT, 2020. Climate ADAPT. https://climate-adapt.eea.europa.eu/metadata/case-studies/irrinet-it-irrigation-system-for-agricultural-water-management-in-emilia-romagna-italy.

Conversa, G., Bonasia, A., Di Gioia, F., Elia, A., 2015. A decision support system (GesCoN) for managing fertigation in vegetable crops. Part II—model calibration and validation under different environmental growing conditions on field grown tomato. Front. Plant Sci. 6, 495. https://doi.org/10.3389/fpls.2015.00495.

Courault, D., Seguin, B., Olioso, A., 2005. Review on estimation of evapotranspiration from remote sensing data: from empirical to numerical modeling approaches. Irrig. Drain. Syst. Eng. 19, 223–249.

de Graaf, R., van den Ende, J., 1981. Transpiration and evapotranspiration of the glasshouse crops. Acta. Hortic. 119, 147–158. https://doi.org/10.17660/ActaHortic.1981.119.13.

De Pascale, S., Rouphael, Y., Pardossi, A., Gallardo, M., Thompson, R.B., 2017. Recent advances in water and nutrient management of soil-grown crops in Mediterranean greenhouses. Acta. Hortic. https://doi.org/10.17660/ActaHortic.2017.1170.3.

Doltra, J., Muñoz, P., 2010. Simulation of nitrogen leaching from a fertigated crop rotation in a Mediterranean climate using the EU-Rotate_N and Hydrus-2D models. Agric. Water Manag. 97, 277–285. https://doi.org/10.1016/j.agwat.2009.09.019.

Doorenbos, J., Pruitt, W.O., 1977. Crop Water Requirements. FAO Irrigation and Drainage Paper No. 24 (rev.). FAO, Rome.

Elia, A., Conversa, G., 2015. A decision support system (GesCoN) for managing fertigation in open field vegetable crops. Part I—methodological approach and description of the software. Front. Plant Sci. 6, 319. https://doi.org/10.3389/fpls.2015.00319.

Elia, A., La Rotonda, P., Lazzizera, C., Conversa, G., 2020a. In press a. Validation of the new modelling for soil water relations and N soil dynamics of the DSS GesCoN: a new release. Acta. Hortic.

Elia, A., Lazzizera, C., La Rotonda, P., Conversa, G., 2020b. In press b. Agronomical effects and response of growers in the application of the GesCoN DSS at the commercial farm scale. Acta. Hortic.

Feller, C., 2015. N-Expert – Fertiliser Recommendations for Field Vegetables. http://www.igzev.de/n-expert/?lang = en . Accessed 2 April 2020.

Feller, C., Fink, M., Laber, H., Maync, A., Paschold, P.-J., Scharpf, H.-C., Schlaghecken, J., Strohmeyer, K., Weier, U., Ziegler, J., 2011. Fertilisation in Outdoor Vegetable Production. Version 7. July 2011. https://www.igzev.de/projekt_type/n-expert-duengung-im-freilandgemuesebau/?lang = en Accessed 28 January 2020. (In German). .

Fereres, E., Goldhamer, D.A., Parsons, L.R., 2003. Irrigation water management of horticultural crops. HortScience 38, 1036–1042.

Fernández, J.E., 2014. Plant-based sensing to monitor water stress: applicability to commercial orchards. Agric. Water Manag. 142, 99–109. https://doi.org/10.1016/j.agwat.2014.04.017.

Fernández, M.D., Baeza, E., Céspedes, A., Pérez-Parra, J., Gázquez, J.C., 2009. Validation of on-farm crop water requirements (PrHo) model for horticultural crops in an unheated plastic greenhouse. Acta. Hort. 807, 295–300. https://doi.org/10.17660/ActaHortic.2009.807.40.

Fernández, M.D., Bonachela, S., Orgaz, F., Thompson, R.B., López, J.C., Granados, M.R., Gallardo, M., Fereres, E., 2010. Measurement and estimation of plastic greenhouse reference evapotranspiration in a Mediterranean climate. Irrig. Sci. 28, 497–509. https://doi.org/10.1007/s00271-010-0210-z.

Fernández, M.D., Bonachela, S., Orgaz, F., Thompson, R.B., López, J.C., Granados, M.R., Gallardo, M., Fereres, E., 2011. Erratum to: measurement and estimation of plastic greenhouse reference evapotranspiration in a Mediterranean climate. Irrig. Sci. 29, 91–92. https://doi.org/10.1007/s00271-010-0233-5.

Fink, M., Scharpf, H.C., 1993. N-expert- a decision support system for vegetable fertilization in the field. Acta. Hortic. 339, 67–74. https://doi.org/10.17660/ActaHortic.1993.339.6.

Fundación Cajamar, 2020. PrHo V. 2,0: Programa De Riego Para Cultivos Hortícolas En Invernadero. https://www.cajamarFundaci.n.es/es/agroalimentario/innovacion/investigacion/documentos-y-programas/ (Accessed 2 April 2020).

Gallardo, M., Snyder, R.L., Schulbach, K., Jackson, L.E., 1996. Crop growth and water use model for lettuce. J. Irrig. Drain. Eng. ASCE 122, 354–361. https://doi.org/10.1061/(ASCE)0733-9437(1996)122:6(354).

Gallardo, M., Thompson, R.B., Valdéz, L.C., Fernandez, M.D., 2006a. Use of stem diameter variations to detect plant water stress in tomato. Irrig. Sci. 24, 241–255. https://doi.org/10.1007/s00271-005-0025-5.

Gallardo, M., Thompson, R.B., Valdez, L.C., Fernández, M.D., 2006b. Response of stem diameter variations to water stress in greenhouse-grown vegetable crops. J. Hortic. Sci. Biotechnol. 81, 483–495. https://doi.org/10.1080/14620316.2006.11512092.

Gallardo, M., Giménez, C., Martínez-Gaitán, C., Stöckle, C.O., Thompson, R.B., Granados, M.R., 2011. Evaluation of the VegSyst model with muskmelon to simulate crop growth, nitrogen uptake and evapotranspiration. Agric. Water Manag. 101, 107–117. https://doi.org/10.1016/j.agwat.2011.09.008.

Gallardo, M., Thompson, B., Fernández, M.D., 2013. Water Requirements and Irrigation Management in Mediterranean Greenhouses: the Case of the Southeast Coast of Spain, in: Good Agricultural Practices for Greenhouse Vegetable Crops. Principle for Mediterranean Climate Areas, FAO, Rome, pp. 109–136.

Gallardo, M., Thompson, R.B., Giménez, C., Padilla, F.M., Stöckle, C.O., 2014. Prototype decision support system based on the VegSyst simulation model to calculate crop N and water requirements for tomato under plastic cover. Irrig. Sci. 32, 237–253. https://doi.org/10.1007/s00271-014-0427-3.

Gallardo, M., Fernández, M.D., Giménez, C., Padilla, F.M., Thompson, R.B., 2016. Revised VegSyst model to calculate dry matter production, critical N uptake and ETc of several vegetable species grown in Mediterranean greenhouses. Agric. Syst. 146, 30–43. https://doi.org/10.1016/j.agsy.2016.03.014.

Gallardo, M., Padilla, F.M., Peña-Fleitas, M.T., de Souza, R., Rodríguez, A., Thompson, R.B., 2020. Crop response of greenhouse soil-grown cucumber to total available N in a Nitrate Vulnerable Zone. Eur. J. Agron. 114, 125993. https://doi.org/10.1016/j.eja.2019.125993.

Gavilán, P., Ruiz, N., Lozano, D., 2015. Daily forecasting of reference and strawberry crop evapotranspiration in greenhouses in a Mediterranean climate based on solar radiation estimates. Agric. Water Manag. 159, 307–317. https://doi.org/10.1016/j.agwat.2015.06.012.

Giménez, C., Gallardo, M., Martínez-Gaitán, C., Stöckle, C.O., Thompson, R.B., Granados, M.R., 2013. VegSyst, a simulation model of daily crop growth, nitrogen uptake and evapotranspiration for pepper crops for use in an on-farm decision support system. Irrig. Sci. 31, 465–477. https://doi.org/10.1007/s00271-011-0312-2.

Giménez, C., Stöckle, C.O., Suárez-Rey, E.M., Gallardo, M., 2016. Crop yields and N losses tradeoffs in a garlic-wheat rotation in southern Spain. Eur. J. Agron. 73, 160–169. https://doi.org/10.1016/j.eja.2015.11.016.

Giménez, C., Thompson, R.B., Prieto, M.H., Suárez-Rey, E., Padilla, F.M., Gallardo, M., 2019. Adaptation of the VegSyst model to outdoor conditions for leafy vegetables and processing tomato. Agric. Syst. 171, 51–64. https://doi.org/10.1016/j.agsy.2019.01.003.

Granados, M.R., Thompson, R.B., Fernández, M.D., Martínez-Gaitán, C., Gallardo, M., 2013. Prescriptive-corrective nitrogen and irrigation management of fertigated and drip-irrigated vegetable crops using modeling and monitoring approaches. Agric. Water Manag. 119, 121–134. https://doi.org/10.1016/j.agwat.2012.12.014.

Grattan, S.R., Bowers, W., Dong, A., Snyder, R.L., Carroll, J.J., George, W., 1998. New crop coefficients estimate water use of vegetables, row crops. Calif. Agric. (Berkeley) 52, 16–21. https://doi.org/10.3733/ca.v052n01p16.

Greenwood, D.J., Lemaire, G., Gosse, G., Cruz, P., Draycott, A., Neeteson, J.J., 1990. Decline in percentage N of C3 and C4 crops with increasing plant mass. Ann. Bot. 66, 425–436. https://doi.org/10.1093/oxfordjournals.aob.a088044.

Hochman, Z., Carberry, P.S., 2011. Emerging consensus on desirable characteristics of tools to support farmers' management of climate risk in Australia. Agric. Syst. 104, 441–450. https://doi.org/10.1016/j.agsy.2011.03.001.

Incrocci, L., Dimauro, B., Santamaria, P., Pardossi, A., 2013. La Concimazione Azotata Degli Ortaggi. Barone e Bella & C.-Ragusa, Italy, pp. 246 In Italian.

Incrocci, L., Massa, D., Pardossi, A., 2017. New trends in the fertigation management of irrigated vegetable crops. Horticulturae 3, 37. https://doi.org/10.3390/horticulturae3020037.

Incrocci, L., Thompson, R.B., Fernández, M.D., De Pascale, S., Stanghellini, C., Pardossi, A., Rouphael, Y., Gallardo, M., 2020. This issue. Irrigation+ management of greenhouse vegetable crops. Agric. Water Manage.

Johnson, L.F., Cahn, M., Martin, F., Melton, F., Benzen, S., Farrara, B., Post, K., 2016. Evapotranspiration-based irrigation scheduling of head lettuce and broccoli. HortScience 51, 935–940. https://doi.org/10.21273/HORTSCI.51.7.935.

Jones, J.W., Hoogenboom, G., Porter, C.H., Boote, K.J., Batchelor, W.D., Hunt, L.A., Wilkens, P.W., Singh, U., Gijsman, A.J., Ritchie, J.T., 2003. The DSSAT cropping system model. Eur. J. Agron. 18 (3), 235–265. https://doi.org/10.1016/S1161-0301(02)00107-7.

Leib, B.G., Elliott, T.V., 2000. Washington irrigation scheduling expert (WISE) software. In: Phoenix, AZ, USA. National Irrigation Symposium, Proceedings of the 4th Decennial Symposium 14–16. pp. 540–548.

Li, J., Song, J., Li, M., Shang, S., Mao, X., Yang, J., Adeloye, A.J., 2018. Optimization of irrigation scheduling for spring wheat based on simulation-optimization model under uncertainty. Agric. Water Manag. 208, 245–260. https://doi.org/10.1016/j.agwat.2018.06.029.

Machet, J.-M., Dubrulle, P., Damay, N., Duval, R., Julien, J.-L., Recous, S., 2017. A dynamic decision-making tool for calculating the optimal rates of N application for 40 annual crops while minimising the residual level of mineral N at harvest. Agronomy 7, 73. https://doi.org/10.3390/agronomy7040073.

Magán, J.J., Gallardo, M., Fernández, M.D., García, M.L., Granados, M.R., Padilla, F.M., Thompson, R.B., 2019. Showcasing a fertigation management strategy for increasing water and nitrogen use efficiency in soil-grown vegetable crops in the FERTINNOWA project. Acta Hortic. 1253, 17–24. https://doi.org/10.17660/ActaHortic.2019.1253.3.

Maltas, A., Machet, J.-M., Le Roux, C., Damay, N., Sinaj, S., 2015. Evaluation of AzoFert®, a software tool for optimizing nitrogen fertilization of Swiss field crops. Recherche Agronomique Suisse 6, 336–345 In French.

Mannini, P., Genovesi, R., Letterio, T., 2013. IRRINET: large scale DSS application for on-farm irrigation scheduling. Procedia Environ. Sci. 19, 823–829. https://doi.org/10.1016/j.proenv.2013.06.091.

Massa, D., Incrocci, L., Incrocci, G., Diara, C., Pardossi, A., 2013. An integrated model for the management of nitrogen fertilization in leafy vegetables. In: D'Haene, K., Vandecasteele, B., De Vis, R., Crapé, S., Callens, D., Mechant, E., Hofman, G., De Neve, S. (Eds.), Proceedings of the NUTRIHORT, Nutrient Management Innovative

Techniques and Nutrient Legislation in Intensive Horticulture for an Improved Water Quality Conference. Ghent, Belgium. pp. 174–178 16-18 September 2013.

Medrano, E., Alonso, F.J., 2007. Programación del riego en cultivos en sustrato. In: Medrano, E., Sánchez-Guerrero, M.C., Lorenzo, P., Alonso, F.J. (Eds.), Relaciones hídricas y programación de riego en cultivos hortícolas en sustratos. IFAPA, Almeria, Spain, pp. 37–42 In Spanish.

Mirás-Avalos, J.M., Rubio-Asensio, J.S., Ramírez-Cuesta, J.M., Maestre-Valero, J.F., Intrigliolo, D.S., 2019. Irrigation-advisor—a decision support system for irrigation of vegetable crops. Water 11, 2245. https://doi.org/10.3390/w11112245.

Montoro, A., López-Fuster, P., Fereres, E., 2011. Improving on-farm water management through an irrigation scheduling service. Irrig. Sci. 29, 311–319. https://doi.org/10.1007/s00271-010-0235-3.

Neale, C.M.U., Jayanthi, H., Wright, J.L., 2005. Irrigation water management using high resolution airborne remote sensing. Irrig. Drain. Syst. Eng. 19, 321–336.

Nendel, C., 2009. Evaluation of Best Management Practices for N fertilisation in regional field vegetable production with a small-scale simulation model. Eur. J. Agron. 30 (2), 110–118. https://doi.org/10.1016/j.eja.2008.08.003.

Olberz, M., Kahlen, K., Zinkernage, J., 2018. Assessing the impact of reference evapotranspiration models on decision support systems for irrigation. Horticulturae 4, 1–14. https://doi.org/10.3390/horticulturae4040049.

Onofri, A., Beccafichi, C., Benincasa, P., Guiducci, M., Tei, F., 2009. Is CropSyst adequate for management-oriented simulation of growth and yield of processing tomato? J. Appl. Hortic. 11 (1), 17–22.

Orgaz, F., Fernández, M.D., Bonachela, S., Gallardo, M., Fereres, E., 2005. Evapotranspiration of horticultural crops in an unheated plastic greenhouse. Agric. Water Manag. 72, 81–96. https://doi.org/10.1016/j.agwat.2004.09.010.

Padilla, F.M., Farneselli, M., Gianquinto, G., Tei, F., Thompson, R.B., 2020. This issue. Monitoring N status of vegetable crops for optimal N management. Agric. Water Manage.

Pardossi, A., Incrocci, L., 2011. Traditional and new approaches to irrigation scheduling in vegetable crops. Horttechnology 21, 309–311. https://doi.org/10.21273/HORTTECH.21.3.309.

Parneaudeau, V., Jeuffroy, M.H., Machet, J.M., Reau, R., Bissuel-Belaygue, C., Eveillard, P., Ostergaard, H.S., Orson, J.A., 2009. Methods for determining the nitrogen fertiliser requirements of some major arable crops. In: Proc. of the International Fertiliser Society, No. 661. International Fertiliser Society. York, UK. pp. 2–26.

Rahn, C.R., Zhang, K., Lillywhite, R., Ramos, C., Doltra, J., de Paz, J.M., Riley, H., Fink, M., Nendel, C., Thorup-Kristensen, K., Pedersen, A., Piro, F., Venezia, A., Firth, C., Schmutz, U., Rayns, F., Strohmeyer, K., 2010. EU-Rotate_N – a european decision support system – to predict environmental and economic consequences of the management of nitrogen fertiliser in crop rotations. Eur. J. Hortic. Sci. 75, 20–32.

Ramírez-Cuesta, J.M., Mirás-Avalos, J.M., Rubio-Asensio, J.S., Intrigliolo, D.S., 2018. A novel ArcGIS toolbox for estimating crop water demands by integrating the dual crop coefficient approach with multi-satellite imagery. Water (Switzerland) 11. https://doi.org/10.3390/w11010038.

Ramos, C., Agut, A., Lidón, A.L., 2002. Nitrate leaching in important horticultural crops of the Valencian Community region (Spain). Environ. Pollut. 118 (2), 215–223. https://doi.org/10.1016/S0269-7491(01)00314-1.

Rhoades, J.D., Loveday, J., 1990. Salinity in irrigated agriculture. Irrigation of Agricultural Crops. American Society of Agronomy, Madison, USA, pp. 1089–1142.

Rinaldi, M., Ventrella, D., Gagliano, C., 2007. Comparison of nitrogen and irrigation strategies in tomato using CROPGRO model. A case study from Southern Italy. Agr. Water Manage. 87 (1), 91–105. https://doi.org/10.1016/j.agwat.2006.06.006.

Smith, M., 1992. CROPWAT. A Computer Program for Irrigation Planning and Management, FAO Irrigation and Drainage Paper no. 46. FAO Land and Water Development Division, Rome, Italy.

Smith, R., Cahn, M., Hartz, T., Love, P., Farrara, B., 2016. Nitrogen dynamics of cole crop production: implications for fertility management and environmental protection. HortScience 2016 (51), 1586–1591. https://doi.org/10.21273/HORTSCI11335-16.

Sonneveld, C., Voogt, V., 2009. Plant Nutrition of Greenhouse Crops. Springer, The Netherlands, pp. 431.

Sonneveld, C., van den Ende, J., de Bes, S., 1990. Estimating the chemical composition of soil solutions by obtaining saturation extracts or specific 1:2 by volume extracts. Plant Soil 122, 169–175.

Soto, F., Gallardo, M., Giménez, C., Peña-Fleitas, M.T., Thompson, R.B., 2014. Simulation of tomato growth, water and N dynamics using the EU-Rotate_N model in Mediterranean greenhouses with drip irrigation and fertigation. Agr. Water Manage. 132 (1), 46–59. https://doi.org/10.1016/j.agwat.2013.10.002.

Soto, F., Gallardo, M., Thompson, R.B., Peña-Fleitas, M.T., Padilla, F.M., 2015. Consideration of total available N supply reduces N fertilizer requirement and potential for nitrate leaching loss in tomato production. Agric. Ecosyst. Environ. 200, 62–70. https://doi.org/10.1016/j.agee.2014.10.022.

Soto, F., Thompson, R.B., Granados, M.R., Martínez-Gaitán, C., Gallardo, M., 2018. Simulation of agronomic and nitrate pollution related parameters in vegetable cropping sequences in Mediterranean greenhouses using the EU-Rotate_N model. Agric. Water Manag. 199, 175–189. https://doi.org/10.1016/j.agwat.2017.12.023.

Steduto, P., Hsiao, T.C., Raes, D., Fereres, E., 2009. Aquacrop-the FAO crop model to simulate yield response to water: I. Concepts and underlying principles. Agron. J. 101, 426–437. https://doi.org/10.2134/agronj2008.0139s.

Stöckle, C.O., Donatelli, M., Nelson, R., 2003. CropSyst, a cropping systems simulation model. Eur. J. Agron. 18 (3), 289–307. https://doi.org/10.1016/S1161-0301(02)00109-0.

Suárez-Rey, E.M., Romero-Gámez, M., Giménez, C., Thompson, R.B., Gallardo, M., 2016. Use of EU-Rotate_N and CropSyst models to predict yield, growth and water and N dynamics of fertigated leafy vegetables in a Mediterranean climate and to determine N fertilizer requirements. Agric. Syst. 149, 150–164. https://doi.org/10.1016/j.agsy.2016.09.007.

Tei, F., de Neve, S., de Haan, J., Kristensen, H., 2020. N management of vegetable crops. Agric. Water Manage This issue.

Thompson, R.B., Gallardo, M., 2003. Use of soil sensors for irrigation scheduling. In: Fernández, M., Lorenzo, P., Cuadrado, I.M. (Eds.), Improvement of Water Use Efficiency in Protected Crops, Dirección General de Investigación y Formación Agraria de la Junta de Andalucía. FIAPA, Spain, pp. 375–402.

Thompson, R.B., Morse, D., Kelling, K., Lanyon, L., 1997. Computer programs that calculate manure application rates. J. Prod. Agric. 10, 58–69. https://doi.org/10.2134/jpa1997.0058.

Thompson, R.B., Martínez-Gaitán, C., Gallardo, M., Giménez, C., Fernández, M.D., 2007. Identification of irrigation and N management practices that contribute to nitrate leaching loss from an intensive vegetable production system by use of a comprehensive survey. Agric. Water Manage. 89, 261–274. https://doi.org/10.1016/j.agwat.2007.01.013.

Thompson, R.B., Gallardo, M., Voogt, W., 2015. Optimizing nitrogen and water inputs for greenhouse vegetable production. Acta. Hortic. 1107, 15–29. https://doi.org/10.17660/ActaHortic.2015.1107.2.

Thompson, R.B., Tremblay, N., Fink, M., Gallardo, M., Padilla, F.M., 2017. Tools and strategies for sustainable nitrogen fertilisation of vegetable crops. In: Tei, F., Nicola, S., Benincasa, P. (Eds.), Advances in Research on Fertilization Management of Vegetable Crops. Advances in Olericulture. Springer, Cham, Switzerland, pp. 11–63.

Thompson, R.B., Incrocci, L., Van Ruijvend, J., Massa, D., 2020. Reducing contamination of water bodies from European vegetable production systems. Agric. Water Manage This issue.

Todorovic, M., Riezzo, E.E., Buono, V., Zippitelli, M., Galiano, A., Cantore, V., 2016. Hydro-tech: an automated smart-tech decision support tool for eco-efficient irrigation management. Int. Agric. Eng. J. 25, 44–56.

van der Salm, C., Voogt, W., Beerling, E., van Ruijven, J., van Os, E., 2020. Minimising emissions to water bodies from NW European greenhouses; with focus on Dutch vegetable cultivation. Agric. Water Manage This issue.

Villalobos, F.J., Delgado, A., López-Bernal, A., Quemada, M., 2020. FertiliCalc: a decision support system for fertilizer management. Int. J. Plant Prod. https://doi.org/10.1007/s42106-019-00085-1.

Villèle de, O., 1972. Besoins en eau des cultures sous serres- Essai de conduite des arrosages en function de l`ensoleollement. Acta Hortic. 35, 123–129 (In French).

Williams, J.R., Jones, C.A., Dyke, P.T., 1984. A modelling approach to determining the relationship between erosion and soil productivity. Trans. ASAE 27, 129–144. https://doi.org/10.13031/2013.32748.