Agricultural Systems 149 (2016) 150–164

Contents lists available at ScienceDirect

Agricultural Systems

journal homepage: www.elsevier.com/locate/agsy

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

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ARTICLE INFO

Article history:
Received 6 January 2016
Received in revised form 12 September 2016
Accepted 17 September 2016
Available online 23 September 2016

Keywords:
Modeling
Simulation models
N management
Vegetable production
KNS-system
Decision support system

ABSTRACT

The EU-Rotate_N and the CropSyst simulation models were evaluated in a Mediterranean climate with two leafy vegetable crops, lettuce and escarole, to simulate (i) dry matter production (DMP), (ii) crop N uptake, (iii) marketable crop production, (iv) soil water content (SWC) and (vi) soil mineral N. Nitrogen (N) treatments were examined in three years with differences in N dose. Relevant parameters were calibrated in both models, especially in the CropSyst simulation model which had not been used before for leafy vegetable crops. For both lettuce and escarole, the EU-Rotate_N model accurately simulated DMP, marketable crop production, crop N uptake and soil mineral N. Simulation of SWC with EU-Rotate_N was statistically acceptable for the upper soil layer for both crops. However, during a rainy period at the end of the escarole crop, SWC was overestimated. In both, lettuce and escarole, the performance of CropSyst to simulate DMP and crop N uptake was acceptable; however, it was consistently poorer than with EU-Rotate_N. In lettuce, CropSyst had a tendency to overestimate DMP and crop N uptake under conditions of no N application (N_0), and to overestimate soil mineral N in the N fertilizer treatments, especially at harvest. In escarole, the simulation of marketable production with CropSyst was poor. In lettuce, simulations of SWC with CropSyst resulted in unacceptable results suggesting the need for CropSyst to be adapted for drip irrigated vegetable crops. Soil mineral N simulations were poorer with CropSyst than with EU-Rotate_N. The results of this work suggest that the overall performance of EU-Rotate_N was superior to CropSyst in both lettuce and escarole in the conditions of SE Spain. The KNS system was used in combination with the EU-Rotate_N model to optimize N management of lettuce. Crop N fertilizer requirements using the KNS system were determined by using simulations with EU-Rotate_N of both crop N uptake and soil mineral N, and the selection of N buffer levels that ensured no commercial yield or quality losses. In the optimal scenario (defined as that which maximized yield with the smaller N application) N fertilizer was reduced by 57% compared to local practices. In addition, soil mineral N and N leaching were reduced by 61% and 57%, respectively, compared to growers' management. This methodology proved to be a useful and easy tool to be used as a Decision Support System (DSS) to program N fertilization in drip fertigated lettuce.

1. Introduction

One of the main challenges of modern agricultural production is to manage crops to ensure high yields with as little negative environmental impact as possible. However, the amounts of nitrogen (N) fertilizer applied to vegetable crops are commonly substantially larger than recommended, considerably exceeding crop N uptake, which can result in high nitrate (NO_3^-) leaching loss (Ramos et al., 2002; Thompson et al., 2007). The reduction and optimization of fertilization has been identified as the most efficient way to improve vegetable production from the environmental perspective (Romero-Gámez et al., 2014).

Lettuce (*Lactuca sativa* L.) and escarole (*Cichorium endivia* L.) are important vegetable crops in Spain. Spain is the world's leading exporting country of lettuce in the world (FAOSTAT, 2011), mainly to other EU countries (FEPEX, 2015), with a national production of 877,000 t in 2012 (MAGRAMA, 2015). Escarole is a leafy vegetable that is attracting increasing interest because of its high nutritive value (Gajc-Wolska et al., 2012). Spanish production of escarole was 59,000 t in 2012 (MAGRAMA, 2015), of which approximately 62% was exported, mainly to other EU countries (FEPEX, 2015).

In the Mediterranean climatic conditions of southeastern (SE) Spain, lettuce is commercially produced on a triple rotation system, with

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http://dx.doi.org/10.1016/j.agsy.2016.09.007
0308-521X/

spring, summer and autumn crops. In this region, N fertilizer management in commercial crops is based on experience rather than on scientific principles. It is common practice that growers use a standard fertilization program that includes weekly N fertilizer application that does not consider crop N demand, nor soil mineral N present at planting or that available to the crop during the period of crop growth. Despite that lettuce production in SE Spain commonly occurs in areas that have been designated Nitrate Vulnerable Zones in accordance with the EU Nitrate Directive (Anon, 1991), the improved N management practices required by the Code of Good Agricultural Practices of Andalusia (BOJA, 2015) are seldom followed. This Code recommends the use of testing for soil mineral N (NO_3^-—N and NH_4^+—N) and consideration of crop N demand to calculate N balances. However, growers in these regions seldom analyze soil mineral N or plant N content to determine N fertilizer rates (Suárez-Rey et al., 2012).

Simulation models can be useful in the development of improved crop N management practices. They enable rapid and repeated calculation of the various transformations which influence crop response to N and the risk of negative environmental impacts. Simulation models may have a part to play with the N management of vegetable crops for which planting dates can vary appreciably; frequent calculation of N requirements is required because of frequent N application through fertigation and to reduce the common occurrence of environmental contamination.

EU-Rotate_N is a simulation model developed to assist with N management in vegetable crop rotations throughout Europe; it is described in detail by Rahn et al. (2010). EU-Rotate_N simulates crop growth and the N and water dynamics in the soil-plant system on a daily basis. The model has been tested with various open field vegetables (Rahn et al., 2010; Doltra and Muñoz, 2010; Nendel et al., 2013) and greenhouse vegetable crops (Guo et al., 2010; Sun et al., 2012; Soto et al., 2014).

CropSyst is an established crop simulation model that may be useful for the N management of vegetable crops. Most studies with CropSyst have been carried out with extensive crops such as wheat, maize, rice, potato, sugar beet, sunflower, barley and soybean (e.g. Stöckle et al., 2003; Benli et al., 2007; Djumaniyazova et al., 2010; Singh et al., 2013). Recently, a module for simulating fruit tree crops was incorporated and evaluated (Marsal and Stöckle, 2012; Samperio et al., 2014). The CropSyst model is composed of a suite of programs, providing a set of tools to analyze the productivity and environmental impact of crop rotations and crop management at different temporal and spatial scales. There has been very little work with CropSyst with vegetable crops, an exception is the study of Giménez et al. (2016) with garlic. In that work, CropSyst was parameterized and verified for a garlic crop in southern Spain, and found to be an adequate tool for evaluating N fertilization strategies. However, there are no published studies with CropSyst with leafy vegetable crops.

Once calibrated and validated, crop simulation models are very useful tools for aggregating knowledge and evaluating scenarios. However, to be used for the practical determination of crop N fertilizer requirements, they need to be used in combination with a N fertilizer recommendation scheme. The KNS system is a simple method for determining N fertilizer applications for vegetable crops and has been successfully used in various northwestern and central European countries/regions, such as Germany (Ziegler et al., 1996), The Netherlands and Flanders, Belgium (Thompson et al., in press). The KNS system is a modification of the N_{min}-method, which was widely used in Germany for determining the N fertilizer recommendations of crops (Wehrmann and Scharpf, 1986).

The KNS method calculates N fertilizer requirements based on species and site specific target N values that are determined for two or more periods during a crop (Lorenz et al., 1989; Thompson et al., in press). The target N value is the sum of crop N uptake and the soil mineral N buffer value for each specific period; the soil mineral N buffer value is the minimum amount of root zone soil mineral N (NO_3^-—N and NH_4^+—N) to ensure that N does not limit crop production. The N fertilizer requirement is calculated by subtracting the measured root zone soil mineral N (NO_3^-—N and NH_4^+—N) from the target N value. Assessments of the N fertilizer requirement (and of the required N target value) are made at planting and once or more during the crop (Thompson et al., in press). Ziegler et al. (1996) described the use of the KNS system with lettuce. Compared to traditional growers' practice, N fertilizer use was reduced by approximately 50% in growers' trials with the KNS system in Germany (Ziegler et al., 1996).

In the work of Ziegler et al. (1996) using the KNS system with lettuce, N fertilizer was applied only as a pre-plant application and as one or two side dressings, so 2–3 soil samplings and analyses were required. In lettuce production in SE Spain, N fertilizer is applied very frequently as part of a nutrient solution applied by combined fertigation and drip irrigation systems. Implementation of the traditional KNS system under these conditions would require frequent and numerous determinations of soil mineral N. The use of simulation models that model soil mineral N and crop N uptake is an approach that may enable the KNS system to be used with fertigated vegetable crops and with crops with different growing seasons. The use of simulation models will enable crop N uptake to be simulated thereby providing greater flexibility than the tabulated values that are otherwise used. Two simulation models that calculate crop N uptake and may be useful when used in combination with the KNS system are the EU-Rotate_N (Rahn et al., 2010) and CropSyst models (Stöckle et al., 2003).

The EU-Rotate_N model is well suited for use in combination with the KNS model to assist with N fertilization recommendations of vegetable crops. It was developed specifically for vegetable production. Like the CropSyst model, it has the optional features of automatic triggers for N fertilization and irrigation events (Rahn et al., 2010; Nendel, 2009) which could be configured for the use with the KNS system with fertigated crops.

The objectives of this work were (i) to calibrate the EU-Rotate_N and CropSyst models for lettuce and escarole grown under Mediterranean conditions in SE Spain, (ii) to evaluate and compare the performance of these two models to simulate seasonal dry matter accumulation, crop N uptake, and soil water and soil mineral N dynamics, and (iii) to use the best-performing model in combination with the KNS system as a DSS to develop a N fertilization program for fertigated lettuce crops that optimizes commercial production whilst minimizing N losses to the environment.

2. Materials and methods

2.1. Site, experiments and cropping details

The experimental work was conducted at the Center for Agricultural Research of IFAPA (Centro Camino de Purchil, Granada, Spain) (37° 10′ N; 3° 40′ W; 640 m altitude). Three spring lettuce crops, Batavian type (cv. Caipira), were grown from 2009 to 2011, and two autumn escarole crops (cv. Mesbella), were grown from 2009 to 2010, on 48 m^2 plots under conditions similar to those of commercial open field conditions in SE Spain. Details of the cropping cycle lengths, irrigation management, and N treatments are presented in Table 1.

The climate in the area is Mediterranean continental temperate with warm summers and cool winters. Daily climatic data (air temperature and relative humidity, rainfall, solar radiation, wind speed and Penman-Monteith reference evapotranspiration) were obtained from a weather station located at the research center. The soil of the experimental field has a loam texture and is classified as Typic Xerofluvent (Soil Survey Staff, 1992). The main soil properties are presented in Table 2.

Above-ground drip irrigation was used. Drip irrigation polyethylene (PE) lines were arranged with 60 cm spacing between laterals, and 33 cm between drip emitters within drip lines, giving an emitter density of 5.1 emitters m^{-2}. The emitters had a discharge rate of 2 L h^{-1}. For both crops, lettuce and escarole, two plant rows, one each side of the