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Prescriptive–corrective nitrogen and irrigation management of fertigated and drip-irrigated vegetable crops using modeling and monitoring approaches

M.R. Granados[a], R.B. Thompson[a,*], M.D. Fernández[b], C. Martínez-Gaitán[a], M. Gallardo[a]

[a] Department of Agronomy, University of Almería, La Cañada 04120, Almería, Spain
[b] Research Station Las Palmerillas, Cajamar Caja Rural, Paraje Las Palmerillas 25, 04710 El Ejido, Almería, Spain

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ABSTRACT

The combined use of fertigation and drip irrigation to frequently apply small amounts of N throughout a crop provides the technical capacity for precise N and irrigation management. A prescriptive–corrective management (PCM) package, based on modeling and monitoring approaches, was developed for combined irrigation and N management to take advantage of this technical capacity in a greenhouse-based vegetable production system. For irrigation, the prescriptive component of PCM was the calculation of historical ETc using the simulation model PrHo to calculate ETc with long term climatic data, and the corrective component was the use of tensiometers. For N, the prescriptive component was based on simulation of crop N uptake, using the simulation model Nup, developed in the present study, and the corrective component was based on controlling soil solution [NO_3^-] in the immediate root zone of the plants. Combined PCM for both N and irrigation management was compared with conventional management (CM) for pepper and muskmelon crops. In both crops, fruit production was very similar in the CM and PCM treatments. Using PCM, total irrigation volume was reduced by 17% in pepper and by 20% in muskmelon; total drainage was reduced by 53 and 49%, respectively. Total applied N was reduced by 35% in pepper and by 29% in muskmelon. Total NO_3^- leaching loss was reduced by 58% in pepper and by at least 49% in muskmelon. The Nup simulation model of crop N uptake was calibrated and validated for pepper and muskmelon. This study demonstrated the effectiveness of combined PCM of both N and irrigation to take advantage of the advanced technical capacity of combined fertigation and drip irrigation systems for precise N and irrigation management.

1. Introduction

Intensive vegetable productions are commonly associated with appreciable negative impacts on water resources through nitrate (NO_3^-) leaching losses and aquifer overexploitation (*e.g.* Ju et al., 2006; Pratt, 1984; Pratt and Adriano, 1973; Ramos et al., 2002; Thompson et al., 2007a). These are consequences of the common tendencies to apply excessive N (Meisinger et al., 2008) and irrigation (Fereres et al., 2003). To appreciably reduce NO_3^- leaching loss, improvement of both N and irrigation management are required (Pratt, 1984). Despite commonly being associated with large NO_3^- leaching loss and other negative effects on water resources, intensive vegetable production systems often have technical characteristics that are well-suited to the adoption of improved N and irrigation management practices.

Greenhouse-based vegetable production on the southeastern (SE) Mediterranean coast of Spain (Castilla, 2002; Pardossi et al., 2004; Castilla and Hernández, 2005), is an example. This system is associated with substantial NO_3^- contamination of underlying aquifers, overexploitation of deep aquifers that supply irrigation water, and a rising water table caused by drainage returns to a shallow aquifer that is increasingly flooding low lying areas (Pulido-Bosch, 2005; Pulido-Bosch et al., 1997). It also has an advanced technical capacity for precise nutrient and irrigation management. Eighty percent of cropping is in soil, the rest in substrate. Soil-grown crops are commonly grown with combined drip irrigation and automatically controlled fertigation systems that apply N and other nutrients, in all irrigations, every 1–3 days (Céspedes et al., 2009; Thompson et al., 2007b). High frequency drip irrigation applying specified N concentrations in all irrigations provides growers with the technical capacity to “spoon feed” both N and irrigation to crops as they are required. Currently, conventional N and irrigation management are based on collective experience using fixed recipes (Thompson et al., 2007b), and this potential for precise N and irrigation management is not being effectively used.

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* Corresponding author at: Department of Agronomy, Escuela Superior de Ingeniería, University of Almería, La Cañada 04120, Almería, Spain. Tel.: +34 950214192; fax: +34 950015939.

E-mail addresses: mgranadosgarcia@cajamar.com (M.R. Granados), rodney@ual.es (R.B. Thompson), mdoloresfernandez@fundacioncajamar.com (M.D. Fernández), cmagaitan@gmail.com (C. Martínez-Gaitán), mgallard@ual.es (M. Gallardo).

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Improved N and irrigation management for practices can be considered as being "prescriptive" or "corrective" (Giller et al., 2004). Prescriptive practices are those in which management follows a program or plan (Giller et al., 2004), corrective practices being those where management is adjusted in response to assessments of crop or soil status of N or water (Giller et al., 2004). "Prescriptive–corrective management" combines both approaches, such that management follows a plan, developed before cropping, to optimize management, and monitoring is subsequently used to make any necessary adjustments to ensure optimal conditions (Giller et al., 2004).

For irrigation, a suitable prescriptive approach for cropping systems with low inter-annual variability of reference evapotranspiration (ETo), as occurs in greenhouses in SE Spain, is the calculation of historical crop evapotranspiration using historical climate data; *i.e.* long term climate averages (Fereres et al., 1981; Hanson and Keita, 1999; Hill and Allen, 1996). For vegetable production in these greenhouses, the simulation model PrHo (Fernández et al., 2001, 2008, 2009) calculates crop evapotranspiration (ETc) from preceding calculations of ETo (Fernández et al., 2010, 2011) and crop coefficient (Kc) values (Orgaz et al., 2005). In these greenhouses, historical ETc agrees well with ETc calculated using measured climatic data (Bonachela et al., 2006). For irrigation, soil water sensors are an established corrective management approach (Evett, 2007; Thompson and Gallardo, 2005). Thompson and Gallardo (2005) suggested that manual tensiometers were effective and economical sensors for soil-grown crops in this greenhouse system. A suggested prescriptive–corrective management system for irrigation for vegetable production in greenhouses in SE Spain is the use of (i) historical ETc, calculated by PrHo, as the prescriptive component, and (ii) manual tensiometers as the corrective component.

For prescriptive N management, simulation of N requirements based on crop N uptake provides sufficient flexibility to consider different planting dates and lengths of growing cycles. As no suitable simulation models were available, the Nup model was developed in the present work. For corrective N management, previous studies in this vegetable production system have demonstrated that soil solution [NO_3^-] could be used to reduce N fertilizer use and NO_3^- leaching loss while maintaining fruit production (Gallardo et al., 2006; Granados, 2011; Granados et al., 2005). Ceramic cup soil solution suction samplers are often used by growers in this system to control soil solution salinity. Sufficiency values of soil solution [NO_3^-] of >5 mmol L^{-1} have been suggested for vegetable crops in California (Burt et al., 1995; Hartz and Hochmuth, 1996) and are used in commercial farming practice in Israel (S. Kramer, Israeli Foreign Ministry, personal communication). [NO_3^-] can be measured on-farm using portable quick test systems (Thompson et al., 2009). A suggested prescriptive–corrective N management system for this vegetable production system is the use of (i) a simulation model to estimate crop N uptake as the prescriptive component, and (ii) monitoring soil solution [NO_3^-] as the corrective component.

The suggested corrective and prescriptive approaches for both irrigation and N management can also be considered as being, respectively, modeling and monitoring approaches. While various studies have evaluated monitoring approaches to N or irrigation management, and some studies have evaluated modeling approaches, few have evaluated combined modeling and monitoring approaches for either irrigation or N management of vegetable crops, and very few, if any, have evaluated modeling–monitoring approaches for combined irrigation and N management.

The primary objective of the current work was to develop a combined prescriptive–corrective management (PCM) system, based on modeling and monitoring, for both irrigation and N management of vegetable crops, and to evaluate this PCM system with muskmelon and pepper crops, assessing its effect on irrigation volume, applied mineral N, drainage volume, NO_3^- leaching, and fruit production. A preliminary objective was to calibrate and validate the Nup model, developed in this work, to simulate crop N uptake of vegetable crops.

2. Materials and methods

2.1. Location and cropping details

A cropping sequence of Galia type muskmelon (*Cucumis melo* L., cv. Deneb) and California sweet pepper crops (*Capsicum annum*, L., cv. Vergasa) were grown in soil in two identical plastic greenhouses at the research station of the Cajamar Foundation, located in El Ejido, in the province of Almeria, southeastern (SE) Spain (2°43′W, 36°48′N and 151 m elevation). For each crop, two treatments of combined irrigation and N management were applied, one in each greenhouse. In one greenhouse, conventional management (CM) of N and irrigation was used, and in the other a prescriptive–corrective management (PCM) treatment was used for N and irrigation management.

The two greenhouses were adjacent to one another along their east–west axis. Each greenhouse was 24 m long by 18 m wide; they were unheated, passively ventilated and had an east–west orientation. The greenhouse cladding was low density polyethylene (LDPE) tri-laminated film (200 μm thickness). Each greenhouse was divided into northern and southern halves by an east–west aligned 1.5 m wide concrete path.

Crops were grown in soil in an artificial layered soil, typical of the region (Castilla and Hernández, 2005; Wittwer and Castilla, 1995), which was formed by placing a 30 cm layer of clay soil, imported from a quarry, over the original sandy loam soil. A 10 cm layer of coarse river sand was placed on the imported clay soil as a mulch. Relevant details of the soil are given in Table 1. Soil depths are expressed relative to the surface of the layer of imported clay soil.

Surface drip irrigation was used, with 1 m spacing between emitter lines and 0.5 m between emitters within emitter lines. The drip emitters had a discharge rate of 2.8 L h^{-1}. The irrigation water had an electrical conductivity of 0.4 dS m^{-1}. Complete nutrient solutions were applied by fertigation through the drip irrigation system, in all irrigations, after the first 15–17 days after transplanting when only water was applied. The nutrient solutions were formulated by injecting concentrated fertilizer solutions into the irrigation water using a programmable fertigation and irrigation controller.

Muskmelon was grown from 14 February 2006 to 23 May 2006, and sweet pepper from 20 July 2006 to 2 February 2007. Six-week old seedlings were transplanted such that individual plants were 6–8 cm from and immediately adjacent to individual emitters giving a plant density of 2 plants m^{-2}. Muskmelon was planted in equidistant parallel lines, and pepper in paired parallel lines by placing seedlings on the inside of each of the paired emitter lines. Plants were vertically supported by nylon cord guides.

In periods of 1–3 days immediately prior to transplanting each crop, pre-transplant irrigations were applied; details are provided subsequently. Between the two crops, chemical soil disinfection was conducted using metham potassium in irrigations of 21 and 18 mm on 8 and 15 June 2006, respectively.

The work was conducted under similar conditions to those of commercial vegetable production on the SE coast of Spain (Castilla et al., 2004; Castilla and Hernández, 2005; Thompson et al., 2007b). All aspects of crop management (training of crop, prunings, pest management, *etc.*) in both the CM and PCM treatments, apart from