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Summer cover crop impacts on soil percolation and nitrogen leaching from a winter corn field

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ABSTRACT

The impacts of a leguminous summer cover crop (sunn hemp; *Crotalaria juncea*) on nitrogen leaching from a corn (*Zea mays* L.) field was evaluated by direct measurements of soil water content and nitrogen balance components, complemented by direct and inverse modeling as an exploratory tool to better understand water flow and nitrogen balances in the soil. Water and nitrogen inputs and outputs were measured during winter corn production in an experimental field located in the south Miami-Dade basin in southern Florida (USA). Data from the last two seasons (2001–2002 and 2002–2003) of a 4-year study are presented. The field was divided into six 0.13 ha plots. One-half of the plots were rotated with sunn hemp (CC plots) during the summer while the remaining plots were kept fallow (NC plots). Sweet corn management was uniform on all plots and followed grower recommended practices. A numerical model (WAVE) for describing water and agrochemical movement in the soil was used to simulate water and nitrogen balances in both types of plots during the corn seasons. The hydrodynamic component of WAVE was calibrated with soil water data collected continuously at three depths, which resulted in accurate soil water content predictions (coefficients of efficiency of 0.85 and 0.91 for CC and NC plots, respectively). Measured components of the nitrogen balance (corn yields, estimated nitrogen uptake, and soil organic nitrogen) were used to positively assess the quality of the nitrogen simulation results. Results of the modeled water balance indicate that using sunn hemp as a cover crop improved the soil physical conditions (increase in soil water retention) and subsequently enhanced actual crop evapotranspiration and reduced soil drainage. However, nitrogen simulation results suggest that, although corn nitrogen uptake and yields were slightly higher in the CC plots than in the NC plots, there were net increases of soil N content that resulted in increased N leaching to the shallow aquifer. Therefore, the use of sunn hemp as cover crop should be coupled with reductions in N fertilizer applied to the winter crop to account for the net increase in soil N content.

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1. Introduction

Agriculture in southern Florida is an important economic activity that competes for land and water resources with ongoing environmental restoration efforts and Miami's urban sprawl. The south Miami-Dade County agricultural region occupies an environmentally sensitive area between the Everglades and the Biscayne National Parks. While agriculture in the area was once perceived as a threat to the fragile natural ecosystems in the National Parks, it is now considered to be a viable alternative to establishment of exotic weeds or Miami's urban sprawl (Ritter et al., 2007). Crop production (vegetables, ornamental and landscape plants, and tropical fruits) in this area occupies approximately 32.4 km^2 located south of the city of Miami (Florida), between the National Parks. The marine subtropical climate of south Florida is conducive to the development of crop diseases and its proximity to South America and several Caribbean countries favors the introduction of new insect pests and invasive plants (Klassen et al., 2002). However, increased pests and low native soil fertility (Potter et al., 2007) have resulted in growers' strong dependence on pesticides and fertilizers to achieve economically sustainable yields.

The shallow unconfined Biscayne aquifer, which underlies the entire region, provides potable water for most of the population residing in southeastern Florida. The aquifer is made of Miami oolite limestone that exhibits extremely high effective hydraulic conductivity values (Fish and Stewart, 1991). The unsaturated zone thickness varies seasonally in the area from 1 to 2 m. Beneath the soil, the limestone is present down to about 12 m where a semi-confining layer is found. The hydrogeology of the area and high rates of fertilizer and pesticide use suggest that farming may be a significant source of non-point source of aquifer pollution. To better understand the environmental costs and benefits of agriculture in this area, the impact of agrochemicals on water resources must be clearly defined. Vegetable growers in Florida's South Dade Basin are commonly advised to maintain vegetative cover crops (CCs) on fields between crops seasons as a best management practice (BMP), and to turn the CC residues into the soil prior to planting (Wang et al., 2002; Li et al., 2006). Sunn hemp (*Crotalaria juncea*) has excellent potential as a CC for this area, because in addition to providing nitrogen fixation as a legume, it has a very rapid growth rate in this climate, thus providing large biomass and a dense cover (Li, 1999). Although it is considered a non-native exotic plant species, sunn hemp does not set seeds in south Florida during the time allotted as a summer CC (from initial seed sowing to mowing). Thus, its potential for becoming an established naturalized species is limited. Benefits attributed to the use of sunn hemp and other CCs are mainly related to the improvement of the soil hydrological and microbiological properties caused by increased soil porosity, reductions in rain drop energy impact at the soil surface, and an increase in soil organic matter content (Reeves, 1994; Rao and Li, 2003; Simonne and Hochmuth, 2003). As a result, herbicide leaching and groundwater contamination may be reduced (Bottomley et al., 1999; Gaston et al., 2003; Harman-Fetcho et al., 2005). Potter et al. (2007) found that the sunn hemp used as a summer crop in rotation with corn in the area effectively reduces atrazine leaching by enhancing rapid and extensive atrazine degradation in soil.

Field-tested computer models can be useful tools for assessing nutrient leaching and devising or demonstrating the efficacy of BMPs to control and reduce negative water quality impacts relative to current practices. In particular, when data is scarce or of limite reliability, physically-based numerical models for water and solute transport can be useful exploratory tools to understand the complexity of these processes and to quantify nitrogen (N) leaching as a consequence of fertilizer practices. However, the use of such models is not an easy task, since they contain a large number of parameters that must be identified before the model can be applied to a specific scenario. The model predictions and associated uncertainties strongly depend on the identification of parameters and model sensitivity to these parameters (Ritter et al., 2003).

The purpose of this study was to evaluate the effectiveness of a summer CC (in this case, sunn hemp) as a BMP to reduce nitrogen leaching from a winter sweet corn crop using a combination of field data and modeling results. The numerical model WAVE (Vanclooster et al., 1996) was selected to simulate water fluxes and nitrate transport through the soil profile to the aquifer. A combination of soil water content time series obtained at different depths and measured components of the nitrogen balance were used to evaluate the model predictions.

2. Materials and methods

2.1. *Experimental site*

The study was conducted in Homestead (80.50°W, 25.5°N), just south of Miami (Florida) on a 4-ha field at the Tropical Research and Education Center (TREC) of the University of Florida (Fig. 1). The topography is essentially flat. The soil is classified as a gravelly loam Krome series (loamy skeletal, carbonatic, hyperthermic, Lithic Undorthents) (Nobel et al., 1996), with average pH of 7.6, electrical conductivity measured in saturated paste extract of 0.33 dS m^{-1}, and a low average organic carbon content around 10 g kg^{-1} (Potter et al., 2007). This is an artificial shallow soil created by ''rock-plowing'' the underlying porous Miami oolite limestone bedrock. Fruit and vegetable fields as well as urban and residential development are found on Krome soils.

2.2. *Experimental setup*

Six experimental plots (47 m × 27 m each) were established on the 4-ha field, with three blocks randomly selected for each BMP treatment (CC) and no cover (NC) crop blocks (Fig. 1). Sweet corn (*Zea mays* L.) was cultivated for a 4-year period in all the plots during the winter months (November to March). Sunn hemp (*C. juncea*) was used as a summer CC. Sunn hemp was planted each year in April to May, after the sweet corn crops were harvested and was tilled into the soil about 1 month prior to planting the sweet corn (October to November). This study focused only on the last 2 years of 4 years of sweet corn/CC rotation, when the nitrogen build-up from the CC

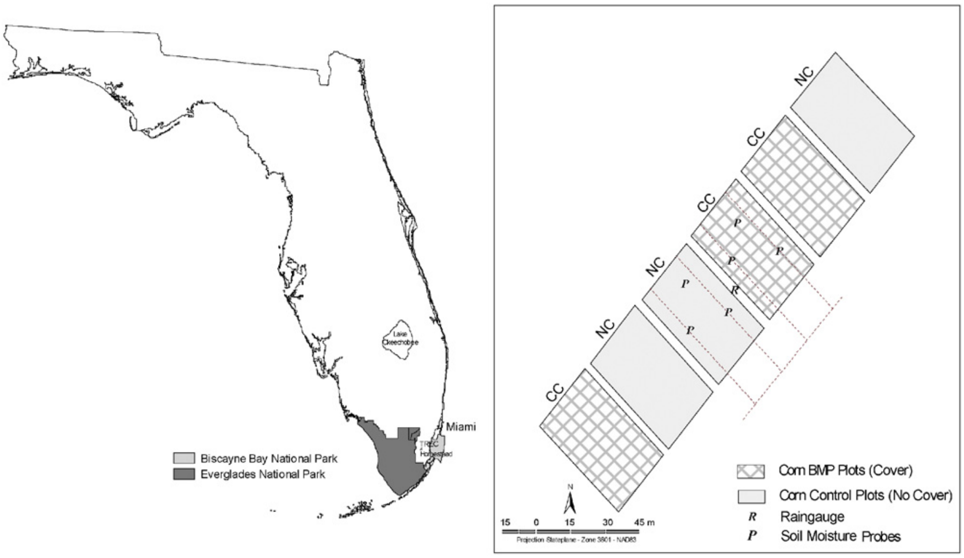

Fig. 1 – Location of UF-TREC and experimental site layout. CC and NC denote plot that was rotated with sunn hemp or kept fallow, respectively.

residue was expected to impact the soil physical characteristics. Sweet corn planting and harvest dates for the first of the last two corn seasons (Season 1) were 28 November 2001 and 4 March 2002 (96 days), while for the last season (Season 2), they were 4 December 2002 and 14 March 2003 (100 days). The sweet corn variety was Attribute^{TM} (Novartis Seeds Inc., Boise, ID) and the crop was managed according to recommended grower's practices in the area (Li et al., 2002). The crop was irrigated through overhead sprinklers when pumping water from a field-irrigation well with a portable pump. Irrigation water was supplied by the solid-set overhead sprinkler irrigation system at an average depth of 8.64 mm/h. The

Table 1 – Parameter estimation and WAVE model sensitivity to the different parameters

Description	Symbol	Process	Sensitivity[a]	Value[b]	Estimation[c]
Crop leaf area index (–)	LAI	Potential transpiration	Medium	(0–2.9)	meas
Crop coefficient (–)	K_c	Crop potential evapotranspiration	High	(0.6–1.1)	meas
Saturated soil water content ($m^3\,m^{-3}$)	θ_s	van Genuchten's retention curve	High	0.467/∼[d]	meas/opt
Residual soil water content ($m^3\,m^{-3}$)	θ_r	van Genuchten's retention curve	Low	0.092	meas
Inverse of the air entry value (cm^{-1})	α	van Genuchten's retention curve	Low	∼	opt
Curve shape parameter (slope) (–)	n	van Genuchten's retention curve	High	∼	opt
Saturated hydraulic conductivity (m day^{-1})	K_s	Unsaturated hydraulic conductivity	Low	∼	opt
Pore connectivity parameter (–)	λ^*	Unsaturated hydraulic conductivity	Low	0.5	lit(1)
Maximum water uptake rate (day^{-1})	S_{max}	Water uptake by roots	Low	0.012	lit(2)
Bulk density (g cm^{-3})	ρ_b	NH_4^+ adsorption	Low	1.41	meas
Hydrodynamic dispersivity (cm)	λ	Convective–dispersive solute transport	Low	3.43	lit(3)
Distribution coefficient of NH_4^+ ($cm^3\,g^{-1}$)	K_d	NH_4^+ adsorption	Medium	0.78	lit(4)
Maximum N uptake (kg ha^{-1})	N_{max}	Nitrogen transformation	Medium	208	lit(5)
Nitrification rate (day^{-1})	k_{nitri}	Nitrogen transformation	Low	0.19	lit(6)
Denitrification rate (day^{-1})	k_{denit}	Nitrogen transformation	Low	0.036	lit(7)
Manure decomposition rate (day^{-1})	k_{man}	Nitrogen transformation	Low	0.011	lit(7)
Litter decomposition rate (day^{-1})	k_{lit}	Nitrogen transformation	Low	0.0099	lit(8)
Humus decomposition rate (day^{-1})	k_{hum}	Nitrogen transformation	Low	0.00011	lit(7)
Carbon turnover efficiency (–)	f_e	Nitrogen transformation	Low	0.4	lit(7)
Humification fraction (–)	f_h	Nitrogen transformation	Low	0.2	lit(7)
C/N ratio of biomass in soil (–)	r_o	Nitrogen transformation	Low	16/18[e]	meas

[a] Model sensitivity (SC) computed as proposed by McCuen (1973), where high: $SC > 1$, medium: $0.5 < SC < 1$, and low: $SC < 0.5$.

[b] ∼ denotes parameter estimated by inverse modeling.

[c] meas: measured; opt: optimized by inverse modeling; lit(#) stands for literature value: lit(1) for Mualem (1976), lit(2) for Vanclooster et al. (1996), lit(3) for Vanderborght and Vereecken (2007), lit(4) for Shinde et al. (2001), lit(5) for Valenzuela and Fox (2005), lit(6) for Riga and Charpentier (1999), lit(7) for Ducheyne et al. (2001) and lit(8) for Dendooven (1990).

[d] For the upper soil layer θ_s was set equal to the measured porosity, but it was optimized for the limestone rock.

[e] $r_o = 16.3$ and 18.4 for the CC and NC plots, respectively.

distribution uniformity of the irrigation system was evaluated in the range 64–79% using a standard catch-can test (ASABE, 2003) in 4 irrigation sub-plots, two of each CC and NC types (Fig. 1). Each year, the number of marketable ears and their length and weight were evaluated on each plot. Yields were comparable to the most successful growers in the region, with no significant difference ($P = 0.05$) in yield, ear length, or weight when CC and NC plot means were compared by two-way ANOVA (Schaffer, unpublished data). After harvest, all plots were mowed and disced repeatedly to turn corn stover into the soil. At the beginning of the following rainy season (early May), Sunn Hemp (Pleasant Valley Farms, Grass Valley, CA or USDA–NRCS, Hilo, HI) was seeded on CC plots at 55 kg ha^{-1}. When the Sunn Hemp was about 1 m tall (end of June), it was mowed to a height of about 0.1 m. By early October, it had regrown to about 1.5 m. The crop was again mowed, and residues were chopped and turned into the soil by repeated discing. In all years, NC plots were left fallow. They were disced before planting and periodically during fallow periods to control weeds. Weeds in the remaining area within the field were managed similarly. N fertilizer during the corn season was split between pre-planting and one or two side-dress broadcast applications followed by cultivation (Table 2). Maximum root depth was surveyed at harvest by pulling out plants.

Meteorological data (15 min) during the study (2001–2003) were collected at the University of Florida's FAWN (Florida Automated Weather Network, http://fawn.ifas.ufl.edu) station located at UF-TREC less than 700 m from the study site. Data were used to compute daily potential evapotranspiration using the Penman–Monteith method (Allen et al., 1998). Soil water was monitored at three soil depths (15, 25, and 35 cm) using six frequency domain reflectometry (FDR) probes (EnviroScan system, Sentek Sensor Technologies, Stepney, Australia) distributed in the plots. A soil specific calibration (Al-Yahyai et al., 2006) was applied and soil water at each depth was obtained by averaging the values measured with the three FDR probes located in each, the CC and NC plots.

Composite disturbed soil samples ($n = 6$) were collected to the limestone surface (0–20 cm) before planting the corn crop and at the end of the experiment. Each sample was obtained by mixing 5 sub-samples randomly collected with an auger soil sampler inside each of the 6 experimental plots. In addition, six undisturbed samples were collected at the beginning of the corn season in 10-cm diameter sampling rings with a sharpened lower edge driven by a centered hammer. All the soil samples were refrigerated in the field with a portable cooler and taken to the analytical laboratory within the same day. Soil texture was determined from the disturbed soil samples following Miller and Miller (1987). Density and porosity were determined from the undisturbed cores following standard methods (Blake and Hartge, 1986; Danielson and Sutherland, 1986). Since calcium carbonate is the basis of these soils, standard analytical methods used to determine organic carbon content (Nelson and Sommers, 1982) over-estimate values. Alternatively, organic carbon was measured in the composite samples via loss-on-ignition analysis, which is based on measuring weight loss after incineration. This value was used to calculate the soil's carbon to nitrogen ratio (C/N) for each treatment. Soil organic nitrogen content was determined on sieved (10 mesh) pulverized samples using a Carlo-Erba Model NA 1500 II carbon–nitrogen analyzer.

2.3. *The numerical model*

The mechanistic–deterministic WAVE model (Vanclooster et al., 1996) was used to describe the water flow and nitrogen transport in the vadose zone. The quality of the numerical solution of this model was successfully tested in a numerical flow and transport modeling benchmark exercise (Vanderborght et al., 2002). Previous studies have successfully applied the WAVE model for describing the water and nitrogen transfers (Riga and Charpentier, 1999; Ducheyne et al., 2001; Duwig et al., 2003; El-Sadek et al., 2003). Additionally, when information about plant phenologic parameters and development is not available, the WAVE model is a suitable alternative

Table 2 – Climatic and management inputs for corn season 1 (2001–2002) and season 2 (2002–2003)[a]

Date	P (mm)	Irr (mm)	ET_c (mm)	T_{min} (°C)	T_{max} (°C)	N fertilizer applications (kg ha^{-1})				
						Urea	$N\text{–}NH_4^+$	$N\text{–}NO_3^-$	Total inorganic N	Organic N
November 2001	0	39	11	14.5	26.2	1.3	27.6	1.3	30.2	5.6
December 2001	39	160	43	15.7	26.1	26.7	22.4	5.9	55.0	39.2
January 2002	26	138	91	13.2	25.7	26.7	22.4	5.9	55.0	39.2
February 2002	104	121	95	14.3	25.2					
March 2002	27	16	126	17.4	27.2					
Season 1[c]	**196**	**474**	**366**	**15.0**	**26.1**	**54.7**	**72.3**	**13.1**	**140.1**	**84.1**
December 2002[b]	53	164	41	14.5	24.8	5.4	132.6	29.1	166.8	22.4
January 2003	10	140	83	9.3	22.0	2.7	55.1	2.7	60.5	11.2
February 2003	43	104	101	14.9	26.8					
March 2003	129	52	120	18.7	29.4					
Season 2[c]	**235**	**460**	**346**	**14.3**	**25.8**	**8.1**	**187.4**	**31.8**	**227.3**	**33.6**

[a] P: precipitation; Irr: irrigation; ET_c: crop potential evapotranspiration; T_{min} and T_{max}: average minimum and maximum temperatures.

[b] Fertilizer application during December 2002 was split in 5 days.

[c] Bold numbers indicate totals or averages for each season.

to other numerical models, because it can still simulate flow and N transfers without modeling crop growth based on generic crop root characteristics, leaf area index and potential crop evapotranspiration.

WAVE describes transient flow by numerically solving the one-dimensional Richards equation (i.e. isothermal Darcian flow equation in a variably saturated, rigid porous medium) plus a sink term describing water uptake by plant roots. The maximum root water uptake is limited by a dimensionless reduction function, which expresses the effect of pressure head on the water uptake rate (Feddes et al., 1978; Hoogland et al., 1980). The soil water retention curve is assumed to be of the form given by van Genuchten (1980), while the unsaturated hydraulic conductivity function is described with the van Genuchten–Mualem model (Mualem, 1976; van Genuchten, 1980).

Considering equilibrium (i.e. homogeneity and perfect solute mixing), the approach for modeling N movement in the soil is based on the convection–dispersion equation (Biggar and Nielsen, 1967). Adsorption of nitrogen species is assumed as a linear, instantaneous and reversible process, where the relationship between the adsorbed and dissolved concentrations is constant. The WAVE model also accounts for transformations of different nitrogen species: organic N, nitrate (NO_3^-), ammonia (NH_4^+) and urea ($CO(NH_2)_2$). Nitrification of NH_4^+, NO_3^- denitrification, and hydrolysis of urea are assessed by first order kinetic approaches. Plant NH_4^+ and NO_3^- uptake is based on maximum N potential uptake rates (i.e. under non-stressed conditions). WAVE simulates plant uptake under stress by specifying the fraction of the total growing season of potential uptake and the calculated convective plant water uptake described before (Feddes et al., 1978; Hoogland et al., 1980). Mineralization of organic N and inmobilization of inorganic N are modeled by using the three pool concept (soil litter, soil humus and soil manure pools). In addition, potential rates for modeling such nitrogen transformations are reduced for temperature and water content in the soil profile. Here, the crop was not modeled and instead the option available in WAVE to compute the soil water and nitrogen balance based on parameters like leaf area index, root system characteristics, and maximum water and nitrogen uptake rates was selected.

In the vertical direction, the model considers the existence of heterogeneity in the form of horizons or layers within the soil profile. These layers are subdivided into space intervals called soil compartments. Halfway in each soil compartment, a node is identified for which the state variables are calculated using a Crank–Nicolson finite difference scheme. To model strongly dynamic processes, such as water, solute and heat transport and solute transformations, a smaller time step can be variably chosen as to limit mass balance errors induced by solving the flow equation. The model inputs are given on a daily basis and outputs can be summed at daily or longer intervals (Muñoz-Carpena et al., 2001).

2.4. Model parameterization

The unsaturated zone thickness simulated was 90 cm with two distinctive layers. The first 20 cm were set as the rock-plowed layer and the remaining thickness (21–90 cm) as the oolitic limestone (Fig. 2). The WAVE model requires a discretization of the domain for the numerical solution. The profile was divided into compartments of 5 cm thickness, the first 4 corresponding to the rock-plowed layer and the rest to the limestone (Fig. 2). The bottom boundary condition for the numerical model was chosen as free drainage. Based on field observations, where roots colonize the plowed layer and extend 5–10 cm into the plow-layer/limestone interface, the maximum root depth was set to 30 cm.

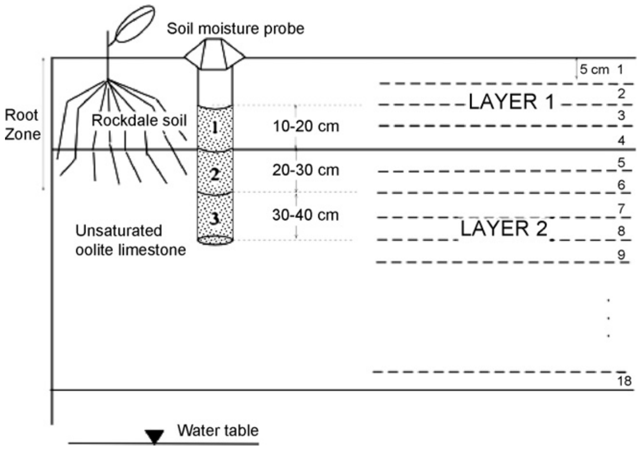

Fig. 2 – Soil discretization used in the models.

Modeling flow and nitrogen transport with WAVE requires a large number of parameters to be estimated; however, the direct estimation of all these parameters is impractical. Instead a combination of parameter identification methods (i.e. experimental estimation and inverse modeling techniques) is often used when applying a numerical model (Ritter et al., 2004). In this context, the parameters most influencing the model response were identified based on the sensitivity coefficient proposed by McCuen (1973), which expresses the percentage rate of variation in the model output per unit of percentage change in a specific parameter. Table 1 summarizes WAVE sensitivity to the parameters studied. Since soil water content time series at different depth were available, we decided to perform the inverse optimization of the parameters that control water movement in the soil, i.e. those with high model sensitivity. In addition, when the model is to be used to simulate effective field conditions, Kutilek and Nielsen (1994) recommended the inverse optimization of the soil water retention curve, instead of using laboratory-determined parameters. Thereby, the van Genuchten–Mualem hydraulic parameters θ_s, α, n and K_s (Mualem, 1976; van Genuchten, 1980) were initially selected for inverse optimization. The remaining parameters were set to measured values or obtained from the literature (Table 1). The leaf area index (LAI) function for sweet corn in the area was adapted from Knisel and Davis (1999) based on typical values for sweet corn in the region. The growing season was divided into 10 equal parts with LAI values of 0.0, 0.09, 0.18, 0.22, 0.40, 1.05, 2.8, 2.85, 2.9, and 1.8 m^2/m^2, respectively. The crop coefficient (K_c) for sweet corn in the area was selected from measured values in the area (Smajstrala, 2000) as 0.6, 1.0, 1.1, 1.0 for each month (December to March). Leaf area index and K_c values between monthly measured intervals were linearly interpolated by the WAVE model. The distribution coefficient for ammonia, K_d, was selected from the transport study of Shinde et al. (2001) conducted using Krome soil from the study area. Maximum N uptake for sweet corn under subtropical conditions was taken from Valenzuela and Fox (2005) as 208 kg ha^{-1} per season. The residual soil water content (θ_r) for the first 20 cm was obtained by gravimetry from soil cores (25 cm diameter and height) packed to the field measured bulk density. The saturated water content (θ_s) is known to be a property with low field spatial variability (Warrick and Nielsen, 1980), therefore, θ_s in the soil layer was set equal to the measured porosity. The physical properties of the limestone rock layer are not well known due to the difficulty in obtaining undisturbed samples of this soft material with an abundance of preferential flow paths. Thereby, θ_s in the rock layer was selected for inverse optimization. The empirical parameters n and α in the van Genuchten's soil water retention curve are shape parameters, so that n represents the slope of the curve, while α is the inverse of the air entry value. Although the WAVE sensitivity to α was low (Table 1) both parameters were selected for optimization to allow for possible changes between both BMP treatments. The K_s exhibits a typical large field variability (Jury et al., 1991; Warrick and Nielsen, 1980) and thus it was selected for inverse estimation. The remaining parameters included in Table 1 were measured or taken from the literature. As a consequence of the limited data available, the estimation of the parameters involved in the N dynamics may be associated with considerable uncertainty. However, several measured components of the N balance (yield-based plant N uptake, N mineralization rates) were used to assess the quality of the simulation results. This approach is practical from a management point of view.

The inverse estimation of the selected hydraulic parameters for the soil and the limestone rock (θ_s, α, n and K_s) was conducted independently with data from both treatment plots. The soil water time series measured at the three depths (15, 25, and 35 cm) were used, where these depths represent the mean of compartments 3–4, 5–6, and 7–8, respectively (Fig. 2). Inverse modeling was first performed for the soil and the limestone rock in the NC plots. For the CC plots, the limestone rock was assumed to have the same parameters (measured and optimized) as the NC plots. In the CC plots, a change in soil water retention was expected because of build-up in organic matter. Therefore, the soil hydraulic parameters were optimized separately for the first and second corn seasons. Intervals delimiting the parameter search space for the inverse optimization were set at (0.30–0.50 m^3 m^{-3}) for θ_s; (1.05–1.50) for n; (0.010–0.250) for α and (0.30–10000 m day^{-1}) for K_s. For each CC and NC treatment, the inverse estimation of the above parameters was performed with only part of the available data set corresponding to Season 1 (2001–2002) and Season 2 (2002–2003), while the remaining data were used for model verification. The calibration periods were selected so that they explored the largest possible range of soil water conditions. Thus, for the NC plots the calibration period was from 20 December 2001 to 25 March 2002, while the verification period was from 27 December 2002 to 21 March 2003. For the CC plots, a calibration and a verification period were established for each corn season. Calibration for Season 1 used measured data from 20 December 2001 to 15 January 2002, plus from 15 to 25 March 2002. The period in between was used for verification. For Season 2, the calibration was performed with the data set corresponding to January 2003, while data collected on February and March 2003 were used for verification.

Table 3 – Measurements of soil organic nitrogen (%) through the experimental period[a]

Date	NC plots	CC plots	$\Delta_{NC\rightarrow CC}$ (%)
October 2000	0.06 ± 0.01	0.06 ± 0.004	–
November 2001	0.08 ± 0.01	0.10 ± 0.01	25
March 2003	0.07 ± 0.001	0.09 ± 0.002	29

[a] Values shown are average ± standard deviation.

Both the forward and inverse simulations were conducted with measured climatic and management data. Table 2 summarizes the monthly average and totals of these values. For the simulation of N dynamics in the soil, the initial organic N content in the litter, humus and manure pools was established based on analysis of soil samples collected at the beginning of each sweet corn season (Table 3). The organic N value measured at the end of the experimental period (March 2003, Table 3) was used for checking the mass balance from the simulation. Corn nitrogen and water uptakes were also estimated based on corn yields and checked against simulation results to assess the performance of the model.

2.5. *Inverse optimization procedure*

The inverse parameter estimation was formulated as a nonlinear optimization problem where the selected model's soil hydraulic parameters were optimized by minimizing the following objective function:

$$\mathrm{OF}(\boldsymbol{b}) = \sum_{j=1}^{m_z}\sum_{i=1}^{m} w_i[\theta^*(z_j, t_i) - \theta(z_j, t_i, \boldsymbol{b})]^2 \qquad (1)$$

where the right-hand side of the equation represents deviations between observed (θ^*) and predicted (θ) space-time soil water using parameter vector $\boldsymbol{b}$, m is the number of measurements over time at each depth and m_z denotes the number of observation depths. The weight of a particular measurement, w_i, denotes the measurement error and was set equal to σ_i^{-2}, where σ is the standard deviation calculated from values obtained with FDR probes at each observation depth. Model adequacy and the uncertainty associated with the estimated parameters were determined according to Hollenbeck et al. (2000) and Ritter et al. (2004). The global optimization algorithm, GMCS, proposed by Huyer and Neumaier (1999) was used to minimize the objective function. Previous studies (Lambot et al., 2002; Ritter et al., 2003, 2004, 2005) showed that the GMCS, combined sequentially with the Nelder–Mead–Simplex (NMS) algorithm (Nelder and Mead, 1965), was a useful tool for estimating the soil hydraulic parameters. The goodness of fit of the simulations with the optimized parameters was evaluated in terms of the coefficient of efficiency, Ceff (Nash and Sutcliffe, 1970), the root mean square error (RMSE), and by visual inspection of the observed and predicted soil water content.

Table 4 – Physical properties of the surface rock-plowed soil layer[a]

Bulk density (g cm^{-3})	1.41 ± 0.01
Specific density (g cm^{-3})	2.67 ± 0.01
Porosity (%)	46.7 ± 1
Texture (%)[b]	
Gravel[c]	51.4
Sand	36.6
Silt	39.6
Clay	23.8
USDA class[d]	G–L

[a] Values shown are average ± standard deviation.
[b] Sand, silt and clay fractions are expressed as percentage of fine material (particle size <2 mm).
[c] Particle size >2 mm.
[d] G = gravelly and L = loam.

3. Results and discussion

3.1. Vadose zone characterization

Physical properties from the laboratory analyses of the upper soil layer are summarized in Table 4. The soil contained 51% porous gravel and 49% of fine material (<2 mm in diameter).

Results from the optimization of the WAVE model parameters are summarized in Table 5. The optimized saturated hydraulic conductivity presented high values for both CC and NC treatments and both layers. Previous studies gave a large range to the K_s, 500–7600 m day^{-1} or above in karstic conditions (Fish and Stewart, 1991). It should be noted that the optimized K_s showed large uncertainties. As previously suggested by several authors (Kool and Parker, 1988; van Dam et al., 1992; Ritter et al., 2004), including additional measurements of one or more hydraulic variables (i.e. matric pressure head or drainage) would be desirable for improving the inverse estimation of this parameter. The saturated water content (θ_s) for the limestone rock and the soil were 0.406 and 0.470 m^3 m^{-3}, respectively. These values are in agreement with the porosity values of this soil ranging from 35% to 45% reported by Fish and Stewart (1991).

Figs. 3 and 4 show the observed and simulated (using the parameters in Table 5) soil water content at the three monitoring depths for the NC and CC plots. Measurement error envelops for observed values are also included. These were obtained from the instrumental error by considering ±0.02 m^3 m^{-3} sensor's accuracy provided by the manufacturer. The visual inspection of these figures indicates that the WAVE model described observed soil water satisfactorily and within the uncertainty bounds of the measured data. The good match between predicted and observed values was supported by the computed goodness of fit criteria. For the NC plots the model performance was quantified with a Ceff of 0.918 and 0.911 for the calibration and verification periods, respectively. The expected error (RMSE) in predictions for both periods was 0.008 and 0.006 m^3 m^{-3}, respectively. Similarly, for the CC plots the calibration and verification periods yielded Ceff = 0.914; RMSE = 0.009 m^3 m^{-3} and Ceff = 0.846; RMSE = 0.009 m^3 m^{-3}, respectively. Although the applicability of Richards equation for very coarse soils could be questionable, these results show that the inverse calibration of parameters under constraints based on physically acceptable ranges is a practical method that can lead to the identification of acceptable effective soil parameters and good simulation results. In a previous study, Duwig et al. (2003) also evaluated satisfactorily the performance of the WAVE model for predicting flow and nitrogen transfer in a soil with large gravel content. As highlighted by the authors, the presence of porous gravel confers the soil particular hydraulic properties that lead to high effective K_s values but they concluded that the simulation results were good and the model was found to be robust enough for these conditions.

3.2. Soil water balance and drainage predictions

Plotting the optimized soil water release curves for each layer and treatment (Fig. 5) shows that the limestone layer exhibited lower porosity than the upper soil layers. As the soil drained (increased suction values), the soil water content depleted quickly in the NC plots while it was released slowly in the CC plots. This effect was further increased in the second season for the CC soil. The different parameter sets for seasons 1 and 2 in those plots where the CC was used (CC) reflect the effect that the increase in soil organic matter content (Table 3) has in the water retention capacity of the soil, i.e. increases the soil aggregation and abundance of water holding pores (pore sizes below field capacity). This conceptually translates into "flattening and raising" of the CC curves with respect to the initial NC status as organic matter accumulates (Fig. 5). This change in the shape of the CC curves is related to larger α values and smaller n values (flatter slope) with respect to the NC curve. These trends are observed in Table 5. Although the change in α between NC and CC is not significant for season 1 (ranges overlap), it is clear in season 2. This implies that after 3 years of continuous rotation, the CC introduced observable changes in the soil that affected the soil water retention (content) time series, as observed in Figs. 3 and 4. The effect of the hydraulic change was most apparent in the surface 10 cm, where soil water in the CC plots was consistently greater than that observed in the NC plots (Figs. 3 and 4).

Table 5 – Results for the optimized and directly determined soil hydraulic parameters[a]

Treatment	Season	Layer	θ_r (m^3 m^{-3})	θ_s (m^3 m^{-3})	α (cm^{-1})	n	K_s (m day^{-1})
NC and CC	Season 1 and 2	Limestone	0.092	0.406 ± 0.046~	0.117 ± 0.061~	1.12 ± 0.03~	8978 ± 4990~
NC	Season 1 and 2	Soil	0.092	0.470	0.093 ± 0.031~	1.22 ± 0.03~	516 ± 348~
CC	Season 1	Soil	0.092	0.470	0.075 ± 0.019~	1.13 ± 0.01~	1545 ± 968~
CC	Season 2	Soil	0.092	0.470	0.204 ± 0.031~	1.09 ± 0.002~	1054 ± 222~

[a] ~ denotes inverse estimated parameter including 90% confidence intervals.

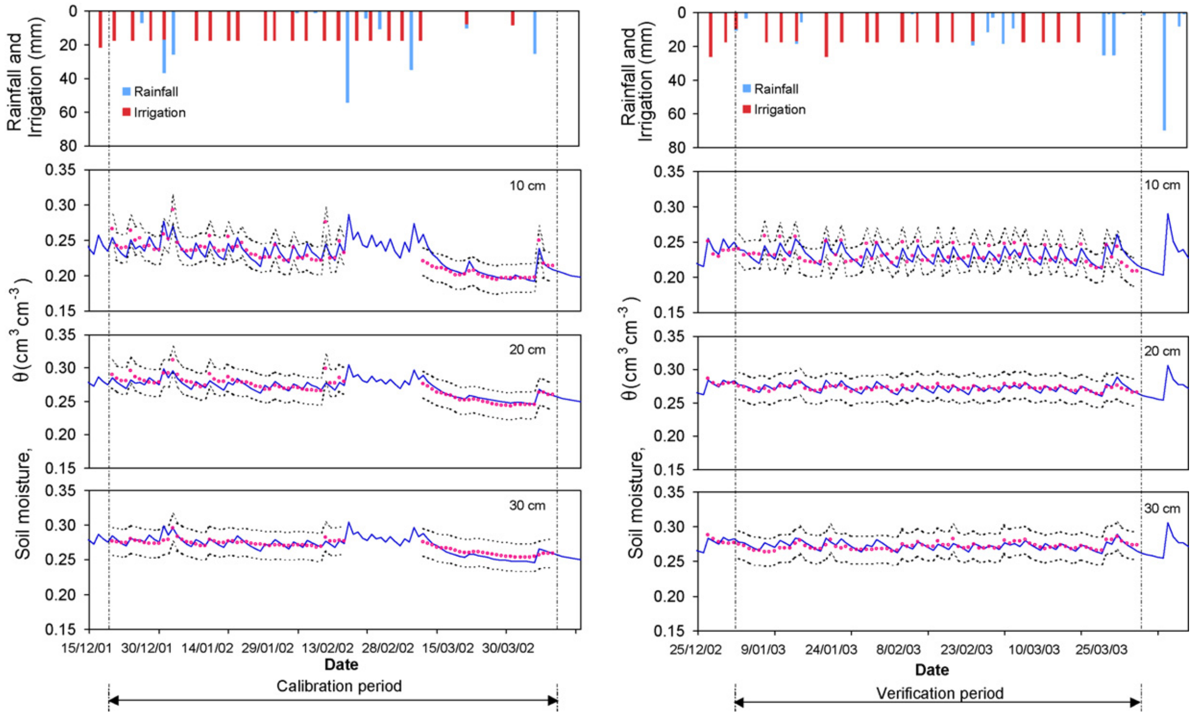

Fig. 3 – Soil water simulation for the NC plots using the optimized parameters (Table 5) for 2001–2002 (left) and 2002–2003 (right) seasons. Measured data (symbols) and WAVE model predictions (lines). The solid lines represent the model simulations using the optimized values, and the dotted lines the uncertainty in the measured values based on ±0.02 $m^3\ m^{-3}$ sensor's accuracy.

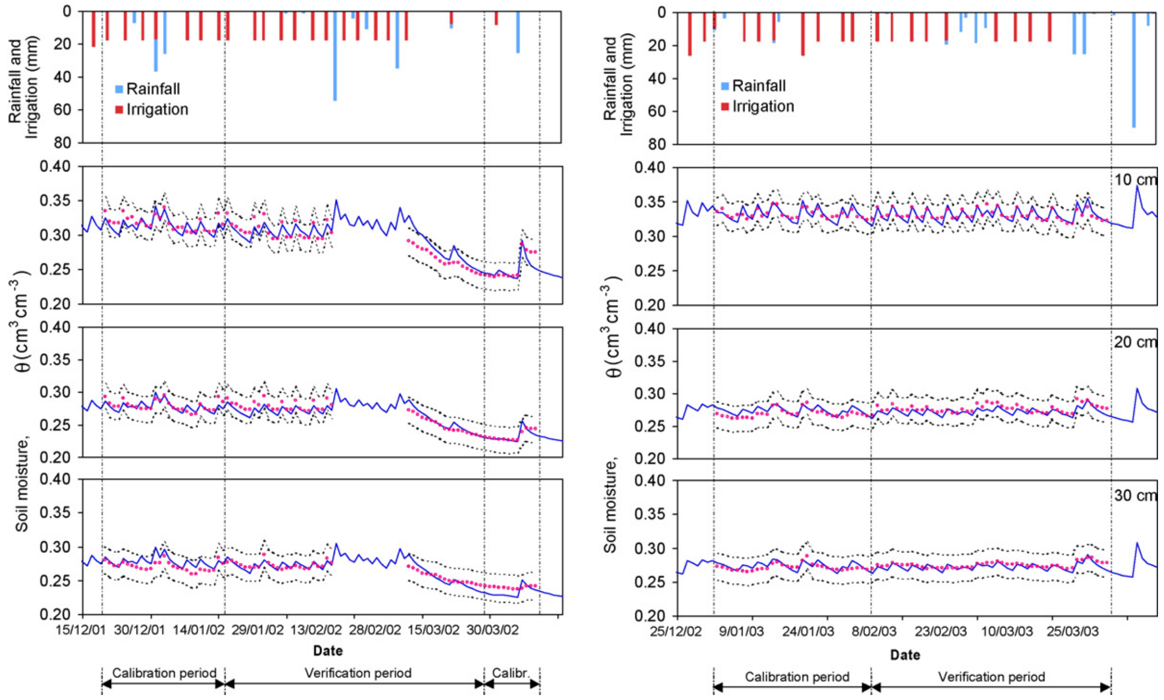

Fig. 4 – Soil water simulation for the CC plots using the optimized parameters (Table 5) for 2001–2002 (left) and 2002–2003 (right) seasons. Measured data (symbols) and WAVE model predictions (lines). The solid lines represent the model simulations using the optimized values, and the dotted lines the uncertainty in the measured values based on ±0.02 $m^3\ m^{-3}$ sensor's accuracy.

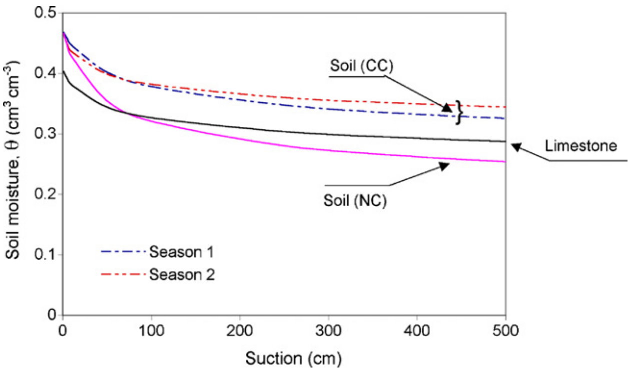

Fig. 5 – Soil water retention curves obtained by inverse optimization for the different layers and BMP treatments.

Precipitation and irrigation over the two growing seasons were 671 and 695 mm, respectively. WAVE drainage predictions at the bottom of the profiles show small reductions in drainage due to the CC (−2 and −1% for seasons 1 and 2, respectively) (Table 6). Notice that drainage totals represent a large portion (around 70% and 60% for seasons 1 and 2, respectively) of all the water input into the soil (precipitation + irrigation). This clearly illustrates over-irrigation as a potential and recurrent water management shortcoming in this area, partly justified by relatively low soil water holding capacity and very high permeability.

Potential Penman–Monteith crop evapotranspiration, ET_c for the two simulation periods was 366 and 346 mm, respectively. The WAVE model predicted actual evapotranspiration (ET_a) values as 73–86% of the ET_c. For season 1 only, ET_a was 10% higher in the CC than the NC plots (Table 6). The higher water holding capacity exhibited by the surface soil at the CC plot allowed for more water to be available for ET_a at times when water content became limiting. Since total water input was increased in the second season, limiting water conditions were not present and the enhanced water retention of the plots with the CC did not play a role in the final ET_a values. Net water storage for the whole simulated profile in season 2 increased 84% and 109% for NC and CC, respectively, when compared to those of season 1. The sunn hemp CC resulted in a change of the soil physical conditions that translated into a reduction in deep drainage, enhanced ET_a and increased water holding in the soil during the corn growing period.

3.3. *Nitrogen balance and leaching*

Total N leached from the soil is a function of the inorganic and organic fertilizer applications (Table 2), organic N content of the soil (Table 3), plant uptake and transformation of the different soil N species into NO_3^- (mineralization rates of organic N, hydrolysis of urea, nitrification), and losses (denitrification, volatilization). Based upon the hydrologic optimization and the chemical transport parameters derived from observed data and the literature, the simulated N balance provided useful qualitative estimates of N transport. The mass error of the N balance reported by WAVE in all simulations was less than 3% of the nitrogen inflow. In an attempt to verify the reliability of the model predictions, the simulations results were compared with available information. Valenzuela and Fox (2005) estimated a net N plant uptake as 208 kg ha^{-1} per season for sweet corn under subtropical conditions and an optimal yield of 20 T ha^{-1} fresh weight. In the present study, total corn yields obtained for both seasons (14.1 and 19.5 T ha^{-1}, respectively) were comparable with grower's yields in the area (14.1–21.2 T ha^{-1}, Li et al., 2002). Although CC treatments yielded about 15% more than NC treatments, these differences were not statistically significant ($P > 0.05$). On the basis of these yields, N uptake per season was calculated as 147 and 203 kg ha^{-1}, respectively. These values are in close agreement to those obtained from the simulations (Table 6). On the other hand, organic N mineralization rates obtained with the WAVE model for both seasons at the NC plots were 121 and 96 kg ha^{-1}, while in the CC plots these values increase to 149 and 134 kg ha^{-1}, respectively. The difference between both treatments matches approximately the 36 kg ha^{-1} (after 15 weeks and considering ambient temperature) that result from applying the empirical potential equation ($R^2 = 0.99$) proposed by Rao and Li (2003) for predicting the organic N mineralization rate from sunn hemp litter in a Krome soil. Additionally the rapid urea hydrolysis and organic N mineralization rates, typical of the dominant hot and humid conditions in the area, contributed to the availability of N uptake and leaching. Interestingly, the organic N values obtained at the end of the simulation for season 2 (March 2003) matched closely (<9% difference) those measured in the field (Table 3) for both NC and CC plots. These results, in combination with the simulated uptake, lend confidence in the modeling of the N balance by WAVE under our experimental conditions.

Since the amount of fertilizer applied to both plots was the same, it follows that simulated differences in estimates of N

Table 6 – Summary of simulation results

Output	Season 1			Season 2		
	NC	CC	$\Delta_{NC\rightarrow CC}$ (%)	NC	CC	$\Delta_{NC\rightarrow CC}$ (%)
Deep drainage, D (mm)	479	470	−2	410	408	−1
Actual ET, ET_a (mm)	260	288	10	297	280	−6
N uptake (kg ha^{-1})	159	183	13	197	206	4
N leaching, L (kg ha^{-1})	42	40	−3	54	62	13
Average [N] leaching, L/D (mg l^{-1})	8.7	8.6	−1	13.3	15.3	13

Simulation periods were from 25 November 2001 until 31 March 2002 (season 1) and from 1 December 2002 until 31 March 2003 (season 2).

leaching and uptake (Table 6) were due to the changes introduced by the CC, namely an increase in organic content (Table 3), ensuing N mineralization, and changes in drainage characteristics. As the organic matter accretion in the soil progressed, i.e. during season 2, drainage and N leaching followed opposite trends. While drainage, as discussed above, tended to decrease in the CC plots, N leaching increased. The increase in average N concentration for the second season, calculated as the ratio between total leaching and drainage, augmented to 13%. This N increase suggests that if the enrichment of N in the soil is not taken into account when managing the crop in rotation with the summer CC, negative environmental effects can be expected. Therefore, it is strongly recommended that when introducing a sunn hemp summer CC as a BMP, N fertilizer rates be reduced with respect to existing recommendations for conventional sweet corn production in the area.

4. Conclusions

The combination of experimental measurements and a state-of-the-art inverse optimization procedure used to determine the hydraulic parameters for the WAVE model yielded good estimates of soil water variation when compared to measured values for the 2001–2002 and 2002–2003 corn growing seasons. A change of soil physical properties was found in corn plots in continuous rotation with a leguminous summer CC after 3 years. These changes are attributed to an increase in organic matter content in the field. Inverse simulation results revealed an increase in water holding capacity that translated into a reduction in soil drainage to the shallow aquifer and an increase in actual evapotranspiration by the crop at the end of the 3 year rotation with the CC. Observed and simulated hydraulic changes were greatest for the top 10 cm of the soil profile where increases in organic matter are more likely to occur.

The nitrogen (N) balance for the corn was also modified as a result of the increased organic nitrogen in the soil. Although corn N uptake and yields slightly increased in the CC plots, so did N leaching (loading) to the shallow aquifer due to the excess of nitrogen available in the profile and fast mineralization and nitrification rates. In fact, the increase in available nitrate in the profile augmented the average concentration of the leached N (13%), thus counteracting the potential benefit introduced by the reduction in drainage and enhanced evapotranspiration resulting from adding the CC. Based on these results, it is recommended that the use of this summer leguminous CC as a potential BMP in the area be coupled with a reduction in N fertilizer application rates during the winter crop to account for the net increase in soil N content.

The modeling scenarios developed here provide a means of examining the rate at which water and subsequently soluble chemicals are transported from the surface of the soil to the groundwater. Thus, they provide the framework for examining additional BMPs for the region. Along with the CC BMP, an additional practice, which appears to hold promise, is irrigation management. Observations made in this study indicate that crops in the region may be significantly over-irrigated. Because of the low water holding capacity and the high saturated hydraulic conductivity of the vadose zone, it is critical to properly manage irrigation in this region.

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