# Calibration of WAVE in irrigated maize: fallow vs. cover crops

J.L. Gabriel , M. Quemada , J. Vansteenkiste , J. Diels , M. Vanclooster

**Abstract**

Nitrate leaching decreases crop available N and increases water contamination. Replacing fallow by cover crops (CC) is an alternative to reduce nitrate contamination, because it reduces overall drainage and soil mineral N accumulation. A study of the soil N and nitrate leaching was conducted during 5 years in a semi-arid irrigated agricultural area of Central Spain. Three treatments were studied during the intercropping period of maize (*Zea mays* L.): barley (*Hordeum vulgare* L.), vetch (*Vicia villosa* L.), and fallow. Cover crops, sown in October, were killed by glyphosate application in March, allowing direct seeding of maize in April. All treatments were irrigated and fertilised following the same procedure. Soil water content was measured using capacity probes. Soil $N_{min}$ accumulation was determined along the soil profile before sowing and after harvesting maize. Soil analysis was conducted at six depths every 0.20 m in each plot in samples from 0 to 1.2-m depth.

The mechanistic water balance model WAVE [1] was applied in order to calculate drainage and plant growth of the different treatments, and apply them to the N balance. We evaluated the water balance of this model using the daily soil water content measurements of this field trial. A new Matlab version of the model was evaluated as well. In this new version improvements were made in the solute transport module and crop module. In addition, this new version is more compatible with external modules for data processing, inverse calibration and uncertainty analysis than the previous Fortran version.

The model showed that drainage during the irrigated period was minimized in all treatments, because irrigation water was adjusted to crop needs, leading to nitrate accumulation on the upper layers after maize harvest. Then, during the intercrop period, most of the nitrate leaching occurred. Cover crops usually led to a shorter drainage period, lower drainage water amount and lower nitrate leaching than the treatment with fallow. These effects resulted in larger nitrate accumulation in the upper layers of the soil after CC treatments.

## 1. Introduction

Agriculture in irrigated semiarid areas is often a source of groundwater contamination. Indeed the great yield potentials driven by extended frost-free periods and abundant solar radiation often results in large fertilization rates which are often unbalanced with the crop assimilation capacity [2]. A good example of such a problematic cultivation system is maize cropping in the Mediterranean area [3][4]. Although adjustments of N applications to the maize crop requirements can reduce $NO_3^-$ losses [5], fertilizer recovered by the maize plants is usually less than 50% [6], leaving a large residue of $N_{min}$ in the soil after harvesting that it is prone to leaching. Introducing a cover crop (CC) during the intercrop period is one of the solutions proposed for reducing the residual $N_{min}$ and hence N leaching [7].

Winter CCs have been developed principally in agricultural systems where the main crop is grown during the summer and the winters are relatively mild and not very dry, allowing a reasonable establishment. Winter CC also reduces soil erosion [8] and run off, it increases the water infiltration capacity [9], it enhances water retention capacity [10][11], it controls weed development [12][13], it suppresses diseases [14], it corrects saline soil [15], and it increases the organic matter and the soil fertility [16][17][18][19]. However, CCs have been sometimes limited in dry regions because they can compete for water resources and nutrients if they are not killed at the correct time [20][21][22]. But in irrigated systems, such as maize cropping systems in the Mediterranean areas, this competence can be avoided.

Physically based numerical models for soil water movement are useful tools to quantify the different terms of the water and nutrient balances in agro-ecosystems [23]. However, the large number of parameters needs appropriate identification before such models can be used in predictive mode [24]. Inverse calibration can help to identify the parameters by an iterative process based, thereby using monitored variables under field conditions [25]. For the parameters driving the water balance, the availability of automated soil moisture probes allowing monitoring soil moisture with a high spatial and temporal resolution supports the adoption of inverse modeling schemes [26].

The main objective of this study was to evaluate the impact of CC in an irrigated maize system on the soil water and nutrient balance terms by means of the calibration of a process based soil water model.

## 2. Materials and Methods

### *2.1. Experimental setup*

The study was conducted on a monoculture of maize (Zea maize L., G-98 Pioneer) in an experimental field station located in Aranjuez (Madrid, Spain) in the Tajo river basin, from October 2006 to April 2010. The soil was a Typic Calcixerept [27] (silty clay loam) and the site is characterized by a Mediterranean semi-arid climate [28]. Temperature, humidity, wind speed, precipitation and solar radiation were recorded hourly with a Campbell Scientific CR23X micrologger (Logan, UT, USA) placed in the experimental field during the study period.

Three treatments and four replications were randomly distributed in twelve plots (12 m x 12 m). The treatments were a barley treatment (*Hordeum vulgare* L., cv. Vanessa), a vetch treatment (*Vicia villosa* L., cv. Vereda) and a fallow treatment (Fig.1). The CC was broadcast by hand and covered by a shallow cultivator after maize harvest and stubble removing on the following dates: 5/10/2006, 11/10/2007, 9/10/2008 and 5/10/2009. At the end of the winter they were killed with one application of glyphosate, leaving the dry residues on the soil (22/3/2007, 24/3/2008, 11/3/2009 and 15/3/2010) and, three weeks later, maize was direct sown over the CC stubble. During the maize period the plots were fertilized with 210 kg N ha$^{-1}$ (ammonium nitrate). Irrigation was only applied during the maize session by a sprinkle

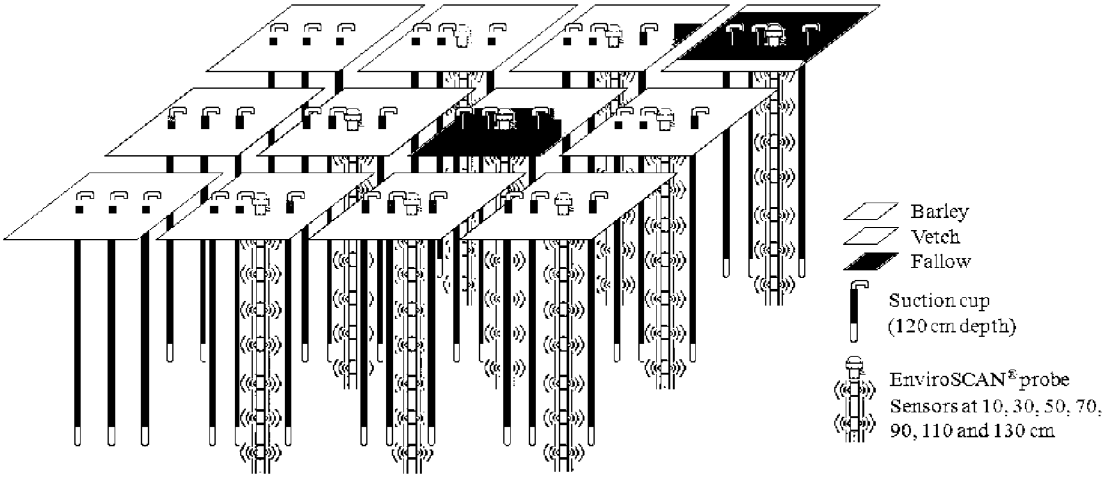


Fig. 1. Experimental setup (each plot was 12 x 12 m$^2$) and distribution of the soil water content sensors and suction ceramic cups.

210 kg N ha$^{-1}$ (ammonium nitrate). Irrigation was only applied during the maize session by a sprinkle irrigation system (12 m x 12 m, 9.5 mm h$^{-1}$) and was adjusted to the evapotranspiration obtained by the FAO method [29], thereby avoiding drainage during these periods. A more detailed description of the experimental site and design can be found in Gabriel and Quemada [30].

*2.2. Direct measurements*

EnviroSCAN® capacitance probes (Sentek Pty Ltd, Stepney, Australia) were used for the daily monitoring of soil water content. Nine probes were installed at three replications for each treatment. Each probe consisted of seven sensors placed every 20 cm from 10 to 130 cm depth. Every sensor was calibrated [31] and readings were registered every hour. Three ceramic suction cups were installed at 120 cm depth in all the plots in order to analyze soil solution, and were sampled every 15 days. Maize and CC LAI measurements were taken along the study period in order to characterize soil coverage, by direct measurement of the leaf surface in maize and with digital images in the CC. Root depth was estimated for each crop from the hourly capacitance sensors data set, based on the differences in soil water content between day and night that were presumably due to plant water uptake. Soil cores were sampled in a trench close to the field experiment in order to measure bulk density, saturated hydraulic conductivity and estimate soil water retention curve parameters. With measured data, probability distribution functions were defined in order to use them for the inverse calibration of the model. A more detailed description of the direct measurements can be found in Gabriel et al. [32].

### 2.3. *WAVE model*

In order to obtain an estimation of the water balance, the soil water module of the WAVE model [1] was inverted using data from the first fallow period (October 2006-April 2007), thereby comparing observed and simulated soil water content at different depths. The soil water modules solve the Richards equation parameterized with a conceptual model for the soil hydraulic properties [33]. The optimized parameters were soil water content at saturation, residual soil water content, hydraulic conductivity and the van Genuchten constants n and $\alpha$, obtaining one value for each parameter and each of the four homogeneous layers (0-20, 20-40, 40-80 and 80-120 cm depth). Subsequently, the plant parameters were calibrated for each CC and for maize, with data from each treatment from October 2006 to April 2007 for the CC and with data from April 2007 to October 2007 for the maize, keeping the soil hydraulic parameters fixed to the previously calibrated values. The parameters adjusted for each crop were i) the date when root reached their maximum inactivity after killing; ii) the maximal root water uptake from each compartment (one for each homogeneous layer); and iii) the four critical pressure heads describing the absorption of water by the plant. Values of LAI, crop coefficient and root depth were based on direct measurements. After that, the model was run for the rest of the experimental period in order to do a validation and to obtain the different terms of the water balance. Nitrate leaching was estimated by multiplying drainage volume obtained with WAVE with the nitrate concentration obtained in the suction cups. A more detailed description of the WAVE application can be found in Gabriel et al. [32].

A new Matlab® (The MathWorks Inc., Natick, MA, USA) version of the WAVE model has also been implemented. This version introduces a generic crop growth module where the growth can be estimated, together with its nitrogen content. The module present a continuous interaction between climate, photosynthesis and plant development stage, based on the Acock formula [34]. Climate time step becomes hourly instead of daily and senescence phenology and partitioning can be simulated now. Moreover, in the water balance module, the potential evapotranspiration is now calculated by application of the FAO estimation [29], instead of being introduced as a climatic input, and there are more boundary condition options. A more detailed description of the Matlab® WAVE version can be found in Van Loon et al. [35].

## 3. Results

The distribution and amount of rainfall and the winter temperatures varied greatly between years, affecting to soil water content and CC growth. The nitrogen uptake by the CC was 157, 39, 39 and 77 kg N $ha^{-1}$ for barley and 179, 20, 56 and 55 kg N $ha^{-1}$ for vetch during the studied periods [30]. The three replications for each capacitance access probe gave results consistent between them. However, some differences in the range maximum-minimum value measured were obtained because local effect of soil cracks and large stones [31], principally in the 0-20 and 40-80 cm depth.

The Fortran WAVE model calibration in the fallow treatment for soil water content resulted in a Nash-Sutcliffe efficiency coefficient ($C_{eff}$) of 0.896 and a root mean squared error (RMSE) of 6.78 mm along the entire profile (Fig. 2). Inverse calibrated parameters (Table 1) were inside the range of data observed in the field [32]. The calibration for the CC resulted in a $C_{eff}$ of 0.841 for the vetch, 0.905 for the barley and 0.860 for the maize, and a RMSE equal to 10.9, 9.0 and 9.5 mm respectively. During the validation periods, modeling error was lower but very close to the error obtained during the calibration period with $C_{eff}$ values of 0.846, 0.826, 0.844 and 0.799 (for fallow, vetch, barley and maize respectively) and RMSE from 7.1 mm in the maize to 11.2 mm in the vetch respectively.

Table 1. The optimized values of soil hydraulic parameters for both WAVE models and of cover crop root parameters. $\theta_r$ was the residual water content, $\theta_s$ the saturated water content, $\alpha$ the inverse of the air entry value, n: curve shape parameter of the water retention model described by Van Genuchten [33], $S_{max}$ the maximum root water uptake by each crop and $h_0$, $h_1$, $h_2$ and $h_3$ the critical-matrix pressure heads defining reduction in water uptake of each crop.

| | | 0-20 cm depth | 20-40 cm depth | 40-80 cm depth | 80-120 cm depth |
|---|---|---|---|---|---|
| $\theta_r$ ($cm^3$ $cm^{-3}$) | FORTRAN | 0.060 | 0.070 | 0.105 | 0.128 |
| | MATLAB | 0.034 | 0.098 | 0.088 | 0.129 |
| $\theta_s$ ($cm^3$ $cm^{-3}$) | FORTRAN | 0.499 | 0.420 | 0.330 | 0.305 |
| | MATLAB | 0.499 | 0.420 | 0.339 | 0.290 |
| $\alpha$ ($cm^{-1}$) | FORTRAN | 0.0124 | 0.0115 | 0.0148 | 0.0340 |
| | MATLAB | 0.0131 | 0.0150 | 0.0149 | 0.0120 |
| n | FORTRAN | 1.441 | 1.283 | 1.172 | 1.190 |
| | MATLAB | 1.422 | 1.307 | 1.170 | 1.157 |
| $K_s$ (cm $day^{-1}$) | FORTRAN | 1009 | 510 | 979 | 525 |
| | MATLAB | 1064 | 547 | 936 | 529 |
| $S_{max}$ ($m^3$ $m^{-3}$ $day^{-1}$) | Vetch | 0.010 | 0.005 | 0.004 | 0.003 |
| | Barley | 0.009 | 0.007 | 0.004 | 0.003 |
| | | $h_0$ (cm) | $h_1$ (cm) | $h_2$ (cm) | $h_3$ (cm) |
| | Vetch | -1 | -29 | -305 | -16797 |
| | Barley | -5 | -31 | -511 | -18296 |

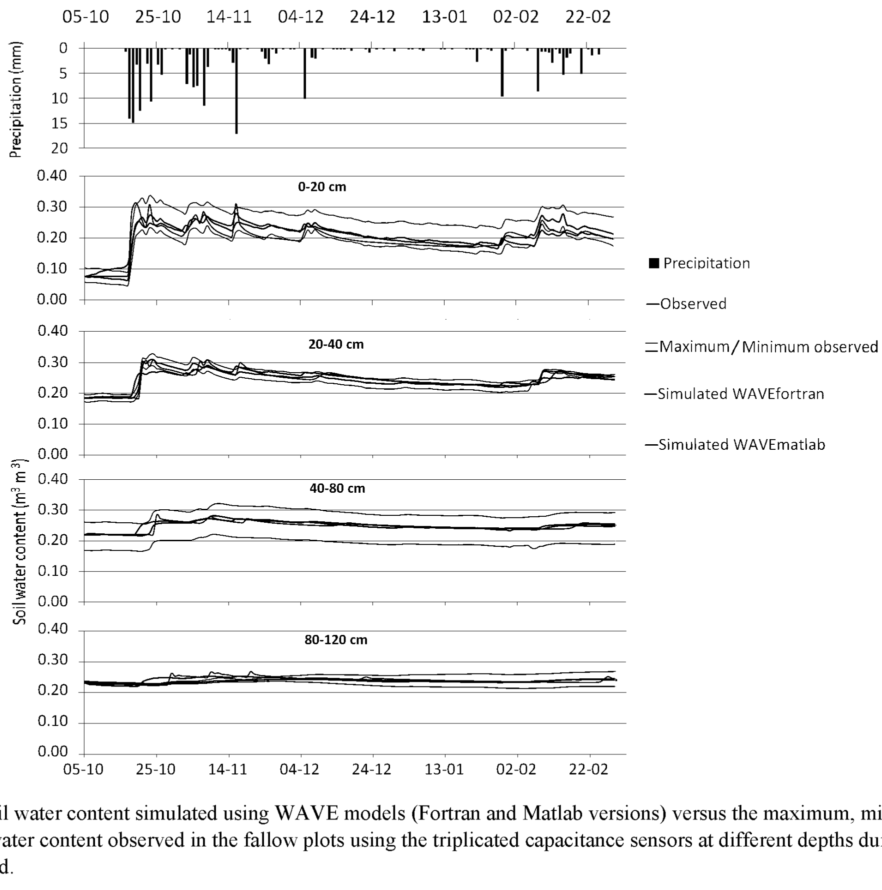


Fig. 2. The soil water content simulated using WAVE models (Fortran and Matlab versions) versus the maximum, minimum and average soil water content observed in the fallow plots using the triplicated capacitance sensors at different depths during the 2006/07 period.

Terms of the water balance are given in Fig. 3. There were large differences during CC periods, mainly because of the weather conditions, but also because of the treatments. Direct evaporation from the soil varied from 51 to 101 mm in the fallow treatment, from 35 to 79 mm in the vetch treatment and from 31 to 65 mm in the barley treatment. On the other hand, transpiration varied from 31 to 108 mm in the vetch treatment and between 41 and 117 mm in the barley treatment, adjusting to the variation observed in the biomass between years and treatments. As a result, the drainage water below 120 cm depth varied from 0 to 314.7 mm in the fallow treatment, between 0 and 301.3 mm in the vetch treatment and between 0 and 233.7 in the barley treatment. The reduction was in agreement with results observed by Thorup-Kristensen et al. [36]. During the maize periods there were no differences between treatments in evaporation or transpiration, but differences in soil water content at sowing time generated differences in drainage (146 mm during the three maize periods in the fallow treatment, 123 mm in the vetch treatment and 86 mm in the barley treatment).

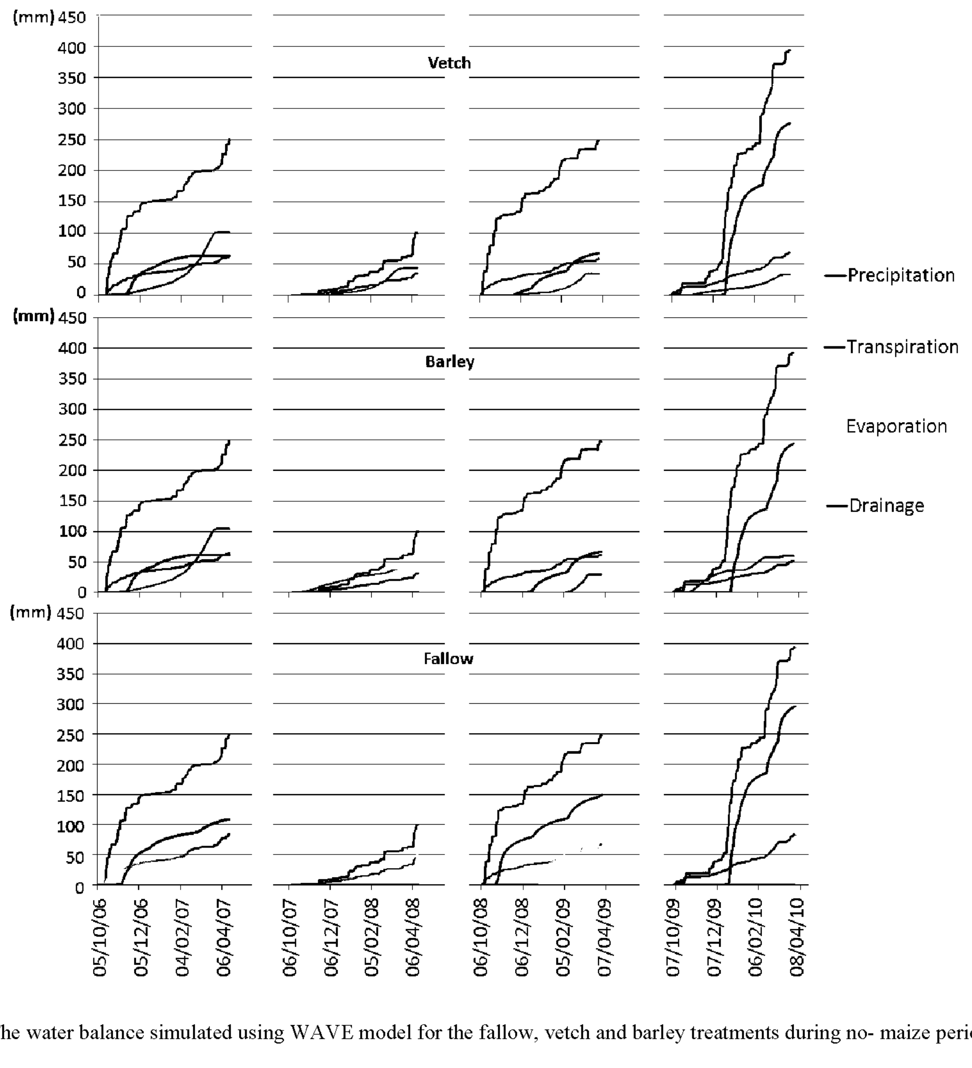


Fig. 3. The water balance simulated using WAVE model for the fallow, vetch and barley treatments during no- maize periods.

Nitrate concentration in drainage was higher in the fallow and vetch treatments than in the barley treatment during almost all the study period, but with a broad range of variation from 0 to 135 mg $N\text{-}NO_3^-$ $L^{-1}$ and usually below 60 mg $N\text{-}NO_3^-$ $L^{-1}$. Multiplying drainage rates with the observed nitrate concentrations yield the nitrate leaching. This resulted in 346 kg $N\text{-}NO_3^-$ $ha^{-1}$ in the fallow treatment during all the study period, 245 kg $N\text{-}NO_3^-$ $ha^{-1}$ in the vetch treatment and only 129 kg $N\text{-}NO_3^-$ $ha^{-1}$ in the barley treatment. These results are consistent with similar studies in more humid regions [7][37].

Results of the implementation of the new Matlab® version of WAVE for the fallow plot are given (Fig. 2). This version of the model presents some small differences in the water balance, mainly because of the change in the way how ET is implemented in the Matlab version. In this latter version, $ET_0$ is not provided as input. ET is directly calculated from energy balance considerations in the soil-crop continuum, needing solar radiation and relative humidity as input. We observe a small increase of accuracy of this new Matlab version ($C_{eff}$ equal to 0.933 and RMSE equal to 5.4 mm for the calibration period and $C_{eff}$ equal to 0.893 and RMSE equal to 8.9 mm considering the four fallow periods together). Moreover, this new version can easier be linked to the advanced data analysis tools available in Matlab, in particularly inverse modeling, sensitivity analysis and uncertainty propagation tools such as SCEM-UA [38]. The implementation of the new crop module is prone to increase the opportunities of application of the model, not only for water and nitrogen balance studies, but also for evaluating crop response processes. Other enhancements of this version is the possibility of running the model during more than a year and including rotations with more than one plant species.

## 4. Conclusions

The physically based agrohydrological model WAVE was successfully implemented for evaluating the impact of cover crops on the water balance and nutrient leaching in irrigated maize cropping systems. Both the Fortran version as well as a newly developed Matlab version of the model was implemented. The latter allows easy data analysis and facilitates advanced modeling analysis (inverse modeling, sensitivity analysis, uncertainty propagation analysis). Inverse modeling with both versions successfully allowed reconstructing measured soil water-content measurements in experimental trials. This good calibration allowed an appropriate quantification of the water balance terms. In combination with observed nitrate concentrations in the suction cups, a reliable quantification of the $NO_3^-$ leaching could be made.

In this irrigated maize system, the CC was able to reduce $NO_3^-$ leaching. Cover crops reduced both the drainage periods and the amount of water drained during those periods. In addition, in the barley treatment, the soil solution $NO_3^-$ concentration was lower than in the fallow or vetch treatment.

Cover crops effectiveness in reducing $NO_3^-$ leaching largely depended on weather conditions. In the Mediterranean regions, the amount and precipitation timing are often very uncertain. Further research will address these issues with the new Matlab version of the model.


## Acknowledgements

Financial support by Spain CICYT (ref. AGL 2011-24732), Comunidad de Madrid (project AGRISOST, S2009/AGR-1630), Belgium FSR 2012 (ref. SPER/DST/340-1120525) and Marie Curie actions.

## References


[1] Vanclooster M, Viaene P, Diels J, Christiaens K. WAVE: a mathematical model for simulating water and agrochemicals in the soil and vadose environment. In: *Reference and user's manual (Release 2.0)*, Institute for Land and Water Management, Katholieke Universiteit Leuven, Belgium; 1996.

[2] Vázquez N, Pardo A, Suso ML, Quemada M. Drainage and nitrate leaching under processing tomato growth with drip irrigation and plastic mulching. *Agri. Eco. and Envir.* 2006;**112**:313-323.

[3] Díez JA, Caballero R, Román R, Tarquis A, Cartagena MC, Vallejo A. Integrated fertilizer and irrigation management to reduce nitrate leaching in central Spain. *J. Environ. Qual.* 2000;**29**:1539-1547.

[4] Causapé J, Quilez D, Aragues R. Assessment of irrigation and environmental quality at the hydrological basin level - II. Salt and nitrate loads in irrigation return flows. *Agricultural Water Management* 2004;**70**:211-228.

[5] Gehl RJ, Schmidt JP, Stone LR, Schlegel AJ, Clark GA. In situ measurements of nitrate leaching implicate poor nitrogen and irrigation management on sandy soils. *J. Environ. Qual.* 2005;**34**:2243-2254.

[6] Bundy LG, Andraski TW. Recovery of fertilizer nitrogen in crop residues and cover crops on an irrigated sandy soil. *Soil Sci. Soc. Am. J.* 2005; **69**:640-648.

[7] Dinnes DL Karlen DL, Jaynes DB, Kaspar TC, Hatfield JL, Colvin TS, Cambardella, CA. Nitrogen management strategies to reduce nitrate leaching in tile-drained Midwestern soils. *Agron. J.* 2002;**94**:153-171.

[8] Hargrove WL. Cover crops for clean water. Soil and water conservation Soc, Ankeny, IA, USA. 1991.

[9] Celette F, Gaudin R, Gary C. Spatial and temporal changes to the water regime of a Mediterranean vineyard due to the adoption of cover cropping. *Eur. J. Agron.* 2008;**29**:153-162

[10] Quemada M, Cabrera ML. Characteristic moisture curves and maximum water content of two crop residues. *Plant Soil* 2002; **238**:295-299.

[11] Ward PR, Flower KC, Cordingley N, Weeks C, Micin SF. Soil water balance with cover crops and conservation agriculture in a Mediterranean climate. *Field Crops Res.* 2012;**132**:33-39.

[12] Derpsch R. Do crop rotation and green manuring have a place in the wheat farming systems of the warmer areas? In: Saunders, D.A. (Ed.), Wheat for the Non-traditional Warm Areas. International Maize and Wheat Improvement Centre (CIMMYT), Mexico. 1990; p. 284–299.

[13] Leavitt MJ, Sheaffer CC, Wyse DL, Allan DL. Rolled winter rye and hairy vetch cover crops lower weed density but reduce vegetable yields in no-tillage organic production. *HortScience* 2011;46:387-395.

[14] Abawi GS, Widmer TL. Impact of soil health management practices on soilborne pathogens, nematodes and root diseases of vegetable crops. *Appl. Soil Ecol.* 2000;**15**:37-47.

[15] Mitchell JP, Shennan C, Peters DW, Miller RO, Prichard T, Grattan SR, et al. Impacts of gypsum and winter cover crops on soil physical properties and crop productivity when irrigated with saline water. *Agric. Water Manage.* 2000;**45**:55-71.

[16] Poudel DD, Horwath WR, Mitchell JP, Temple SR. Impacts of cropping systems on soil nitrogen storage and loss. *Agricultural Systems* 2001;**68**:253-268.

[17] Fageria NK, Baligar VC, Bailey BA. Role of cover crops in improving soil and row crop productivity. *Communications in Soil Science and Plant Analysis* 2005;**36**:2733-2757.

[18] Zhu B, Yi L, Chen G, Hu Y, Tang H, Xiao C, et al. Performance of two winter cover crops and their impacts on soil properties and two subsequent rice crops in Dongting Lake Plain, Hunan, China. *Soil & Tillage Research* 2012;**124**:95-101.

[19] Peregrina F, Pérez-Álvarez EP, Colina M, García-Escudero E. Cover crops and tillage influence soil organic matter and nitrogen availability in a semi-arid vineyard. *Archives of Agronomy and Soil Science* 2012;**58**:95-102.

[20] Unger PW, Vigil MF. Cover crops effects on soil water relationships. *J.Soil Water Conserv.* 1998; 53:200-2007.

[21] Gregory PJ, Simmonds LP, Pilbeam CJ. Soil type, climatic regime, and the response of water use efficiency to crop management. *Agron. J.* 2000;**92**:814–820.

[22] Islam N, Wallender WW, Mitchell J, Wicks S, Howitt RE. A comprehensive experimental study with mathematical modeling to investigate the affects of cropping practices on water balance variables. *Agric. Water Manage.* 2006;**82**:129-147.

[23] Muñoz-Carpena R, Ritter A, Bosch DD, Schaffer B, Potter TL. Summer cover crop impacts on soil percolation and nitrogen leaching from a winter corn field. *Agric. Water Manage.* 2008;**95**:633-644.

[24] Simunek J, Wendroth O, van Genuchten MTh. Soil hydraulic properties from laboratory evaporation experiments by parameter estimation. In: van Genuchten MTh, Leij FJ, Wu L (Eds.), *Proceedings of the International Workshop, Characterization and Measurement of the Hydraulic Properties of Unsaturated Porous Media.* University of California, Riverside, CA. 1999; p. 713-724.

[25] Ritter A, Hupet F, Muñoz-Carpena R, Lambot S, Vanclooster M. Using inverse methods for estimating soil hydraulic properties from field data as an alternative to direct methods. *Agric. Water Manage.* 2003;**59**:77-96.

[26] Fares A, Alva AK. Evaluation of capacitance probes for optimal irrigation of citrus through soil moisture monitoring in an entisol profile. *Irrig. Sci.* 2000;**19**:57-64.
[27] Soil Survey Staff. Keys to Soil Taxonomy. Ninth Edition. USDA, Natural Resources Conservation Service. Madison, WI, USA 2003.
[28] Papadakis J. Climates of the world and their agricultural potentialities. DAPCO, Rome, Italy. 1996.
[29] Allen RG, Pereira LS, Raes D, Smith M. FAO 56 Irrigation and drainage paper: crop evapotranspiration. Food and agriculture Organization. Rome, Italy. 1998.
[30] Gabriel JL, Quemada M. Replacing bare fallow with cover crops in a maize cropping system: Yield, N uptake and fertiliser fate. *Eur. J. Agron.* 2011;**34**:133-143.
[31] Gabriel JL, Lizaso JI, Quemada M. Laboratory versus field calibration of Capacitance Probes. *Soil Sci. Soc. Am. J.* 2010;**74**:593–601.
[32] Gabriel JL, Muñoz-Carpena R, Quemada M. The role of cover crops in irrigated systems: water balance, nitrate leaching and soil mineral nitrogen accumulation. *Agric. Ecosyst. Environ.* 2012;**155**:50–61.
[33] van Genutchen MT. A closed-form equation for predicting the hydraulic conductivity of soil. *Soil Sci. Soc. Am. J.* 1980;**44**:892-898.
[34] Acock B, Charles-Edwards DA, Fitter DJ, Hand DW, Ludwig J, Warren Wilson J, Withers AC. The contribution of leaves from different levels within a tomato crop to canopy net photosynthesis: an experimental examination of two canopy models. *Journal of Experimental Botany* 1978;**29**:815–827.
[35] Van Loon J, Vansteenkiste J, Diels J, Schrevens E. Developing and testing a model for open field horticultural crops to enable use of a 'just-in-time' fertilization management. *19th International Congress on Modelling and Simulation*, Perth, Australia, 2011; p. 1016-1022.
[36] Thorup-Kristensen K, Magid J, Jensen LS. Catch crops and green manures as biological tools in nitrogen management in temperate zones. *Adv. Agron.*2003;**79**:227-302.
[37] Strock JS, Porter PM, Russelle MP. Cover cropping to reduce nitrate loss through subsurface drainage in the northern US Corn Belt. *J. Environ. Qual.* 2004;**33**:1010-1016.
[38] Vrugt JA, Gupta HV, Bouten W, Sorooshian S. A Shuffled Complex Evolution Metropolis algorithm for optimization and uncertainty assessment of hydrologic model parameters. *Water Resources Research* 2003;**39**:SWC11-SWC116.