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Assessing cover crop management under actual and climate change conditions

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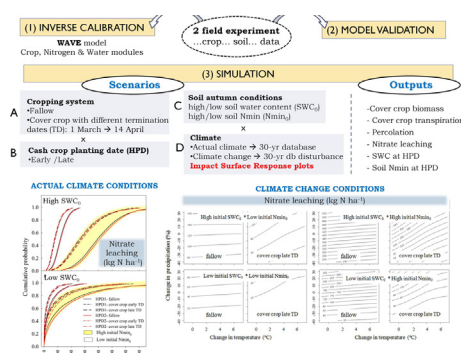
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HIGHLIGHTS

- WAVE model was inverse calibrated and validated with field measurements.
- Impact response surface approach was used to assess future climate scenarios.
- Late cover crop termination reduced leaching but increased competition risk.
- The cash crop planting date was a tool to control preemptive competition.
- Under climate change conditions, cover crop management becomes crucial.

GRAPHICAL ABSTRACT



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ABSTRACT

The termination date is recognized as a key management factor to enhance cover crops for multiple benefits and to avoid competition with the following cash crop. However, the optimum date depends on annual meteorological conditions, and climate variability induces uncertainty in a decision that needs to be taken every year. One of the most important cover crop benefits is reducing nitrate leaching, a major concern for irrigated agricultural systems and highly affected by the termination date. This study aimed to determine the effects of cover crops and their termination date on the water and N balances of an irrigated Mediterranean agroecosystem under present and future climate conditions. For that purpose, two field experiments were used for inverse calibration and validation of the WAVE model (Water and Agrochemicals in the soil and Vadose Environment), based on continuous soil water content data, soil nitrogen content and crop measurements. The calibrated and validated model was subsequently used in advanced scenario analysis under present and climate change conditions. Under present conditions, a late termination date increased cover crop biomass and subsequently soil water and N depletion. Hence, preemptive competition risk with the main crop was enhanced, but a reduction of nitrate leaching also occurred. The hypothetical planting date of the following cash crop was also an important tool to reduce preemptive competition. Under climate change conditions, the simulations showed that the termination date will be even more important to reduce preemptive competition and nitrate leaching.

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1. Introduction

Nitrate leaching from the root zone of agricultural crops puts a major constraint on modern agriculture. Nitrate leaching induces pressure on groundwater systems in agricultural basins and reduces nutrient use efficiency of the agricultural crops. Nitrate leaching is also a specific concern for irrigated agriculture (Causapé et al., 2004; Díez et al., 1997). Even when the fertilization and the irrigation are adjusted to crop demand, it is difficult to obtain N use efficiencies higher than 60% (Dinnes et al., 2002). A great amount of residual nitrate may remain in the soil after harvest (Bundy and Andraski, 2005; Gabriel and Quemada, 2011). This nitrate will then be prone to leaching during the subsequent fallow period. The environmental performance of an irrigated agroecosystem would therefore be considerably improved if nitrate leaching between two cash crops could be reduced.

Replacing the fallow period between two cash crops with cover crops is one of the techniques that is advocated to reduce nitrate leaching in both dry and humid regions (Gabriel et al., 2012b; Hargrove, 1991; McCracken et al., 1994; Thorup-Kristensen et al., 2003). The reduction of nitrate leaching with cover cropping is due mainly to an increased retention of N in the cover crop biomass, the reduction of the nitrate concentration in the percolating water, and/or the reduction of the percolating water flux (Kramberger et al., 2014; Thorup-Kristensen et al., 2003). However, the use of cover crops is still not very popular in arid and semiarid regions because a cover crop is suspected of competing for water and nutrients with the cash crop (Unger and Vigil, 1998). Cover crop management is crucial to avoid such competition, particularly deciding the appropriate termination date (Alonso-Ayuso et al., 2014).

Guidelines for cover crop management are not yet well elaborated (Clark et al., 2007; Krueger et al., 2011). Choosing a termination date, for instance, should consider the balance between often conflicting objectives. On the one hand, a reasonable water and nutrient extraction should be achieved by delaying the termination date, which would reduce nitrate leaching, provide nutrient recycling after residue mineralization, and cover the soil, hence avoiding direct evaporation of the topsoil (Clark et al., 2007). However, as this is a complex system, there is not a universal recommendation for cover crop management (Clark et al., 2007; Krueger et al., 2011). On the other hand, the water and nutrient extraction by the cover crop should be limited by advancing the termination date to avoid competition with the subsequent cash crop. Under various climate scenarios, the uncertainty of the decision taken is expected to increase. Because of that indecision, quantification of potential advantages and disadvantages of various termination dates may contribute to the best practice for cover cropping.

The in situ experimental assessment of the role of cover crops on water and nutrient balances is complicated. This assessment is particularly linked to the difficulty of measuring water and nutrient fluxes in the soil crop continuum (Gehl et al., 2005; Webster et al., 1993). In addition, the experimental approach does not allow evaluation of the possible impacts of cover crops in future changing environments. Hence, as an alternative, water and nutrient balance modeling is often presented to evaluate the effect of different crop management techniques on the functioning of the agroecosystem (Muñoz-Carpena et al., 2008; Tribouillois et al., 2016). The calibration of all the parameters involved in the water and nutrient fate models remains, however, a challenge (Simunek et al., 1999). However, this challenge can be partially addressed by inverse modeling techniques, as well as the combination of field data with modeling techniques (Paramasivam et al., 2001; Ritter et al., 2003).

When appropriately calibrated, field scale water nutrient balance models can be used to evaluate the impact of different cover crop strategies on agroecosystem functioning in an environment where the climate is changing. The evaluation of the impact of climate change on agroecosystem functioning is particularly important for Mediterranean agriculture as the Mediterranean region is considered a hotspot for

climate change. Moreover, an accurate simulation of water and N balances relies on accurate precipitation data. The uncertainty of precipitation projections currently associated with climate model outputs makes exploiting these precipitation projections difficult for many impact studies (Ruiz-Ramos et al., 2016). Other approaches are needed for dealing with this uncertainty, as, for instance, the impact and adaptation response surfaces that provide a wide range of impact responses for a plausible range of futures (Pirttioja et al., 2015; Ruiz-Ramos et al., 2017).

The main goal of this paper is to study the effects of cover crops on the water and N balances of an irrigated Mediterranean agroecosystem under present and future climate conditions. The specific sub-objectives are: i) to calibrate and validate the water and N balance model WAVE (Water and Agrochemicals in the soil and Vadose Environment; Gabriel et al., 2012b; Vanclooster et al., 1996), ii) to analyze the effect of the cover crop termination date and interannual climate variability on potential nitrate leaching and the following cash crop competition; and iii) to analyze the effect of different future climate scenarios on this cover crop effect.

2. Materials and methods

2.1. Field experimental setup

The model was calibrated and validated based on field data from two different experiments. Both experiments were conducted in an experimental field station located in Aranjuez (Madrid, Spain) in the Tajo River basin. The soil was analyzed at the beginning of the experiment (Gabriel et al., 2010) and classified as a *Typic Calcixerept* (silty clay loam) based on Soil Survey Staff (2014). The climate was characterized as a Mediterranean semi-arid climate based on Papadakis (1966). Annual weather information (temperature, humidity, wind speed, precipitation and solar radiation) were recorded hourly with a weather station (Campbell Scientific Inc., Logan, UT, USA) placed in the experimental field.

The first experiment consisted of a 4-year cover crop-maize rotation with three treatments and lasted from October 2006 to October 2010. The treatments considered barley (*Hordeum vulgare* L.), vetch (*Vicia villosa* L.) and fallow during the cover crop period, keeping the maize (*Zea mays* L.) as the main crop during the three summers included in the study. The treatments were randomly distributed in twelve 144 m² plots with four replications, keeping plots constant for the 4 years. The cover crops were sown around the first week of October and terminated with one application of glyphosate between the second and the third week of March. During their growth, cover crops did not receive fertilization or irrigation. A more detailed description of the experimental site and design can be found in Gabriel and Quemada (2011) and Gabriel et al. (2012b).

The second experiment consisted of a 2-year cover crop system (from October 2011 to October 2013) compared with fallow. In this case, the cover crop consisted of a barley-vetch mixture, and the treatments used two different cover crop termination dates: mid-March and mid-April. A cover crop mixture was also sown around the first week of October in twelve 180 m² plots (again randomly distributed with four replications). The termination was made by a glyphosate application, keeping residues over the soil surface. Similarly, cover crops were not fertilized or irrigated. A more detailed description of the experiment is available in Alonso-Ayuso et al. (2014).

2.2. Field measurements

Both plant and soil variables were measured. The cover crop plant measurements in both field experiments consisted of the crop soil coverage (measured every 15 days at five permanent points per plot by taking digital images from a nadir perspective at a 1.5 m height; Ramírez-García et al., 2012), crop phenology, final aerial biomass production and final N concentration in the aerial biomass, to obtain the total N

uptake. Root biomass at harvest was determined only in the 4-year experiment. Soil measurements were soil mineral N as NO_3^- and NH_4^+ (Nmin), soil solution and soil water content (SWC). Soil Nmin was sampled every year before sowing the cover crop and after terminating the cover crop. In the 2-year experiment, samples were collected after the second termination date for all treatments. An helicoidal auger (Eijkkelkamp Agrisearch Equipment, Giesbeek, The Netherlands) was used to obtain 4 cores per plot from 0 to 1.2 m depth at 0.2 m intervals. The four cores were combined by depth, obtaining six composited samples for each plot profile. Each sample was placed in a plastic box, firmly closed, immediately refrigerated (4–6 °C) and extracted within five consecutive days. Extraction was performed with 1 M KCl (~30 g of soil: 150 ml KCl). The extract was centrifuged, decanted and stored in a freezer until analysis. The Griess-Ilosay method (Keeney and Nelson, 1982) was used for the determination of NO_3^- -N concentration and the salicylate-hypochlorite method (Solorzano, 1969) for the determination of NH_4^+ -N. Soil solution at 1.2 m depth was sampled in the 4-year experiment every 15 days or after a 20-mm rainfall event using 3 vertical suction cups per plot. The suction cups (Lord and Shepherd, 1993) were pumped with a hand-operated vacuum that transferred solution to a storage bottle by a capillary tube. The suction was maintained to 333 cm inside the cups between sampling events. Soil solution samples were stored in a freezer until analysis by the same Griess-Ilosay and salicylate-hypochlorite method. Soil water content was monitored hourly using EnviroSCAN capacitance probes (Sentek Sensor Technologies, Stepney, South Australia, Australia) (Arregui and Quemada, 2006; Paltineanu and Starr, 1997). Nine and twelve access tubes were installed in the 4-year and 2-year experiments, respectively. Each access tube consisted of a plastic extrusion with 6 sensors from 0.1 to 1.1 m depth every 0.2 m. Sensors were previously normalized, calibrated (under field and laboratory conditions) and validated by Gabriel et al. (2010). The EnviroSCAN information was also used to estimate the root depth. When a sensor showed water depletion during the day but not during the night, water was assumed to have been lost by transpiration inside the sensor sphere of influence. Therefore, the sensor depth was considered to be within the active root zone. From this time and during the same growing season, the depth was assumed to be either maintained or increased but never reduced. More details of the field measurements for both experiments are available in Gabriel and Quemada (2011) and Gabriel et al. (2012b) for the 4-year experiment and in Alonso-Ayuso et al. (2014) for the 2-year experiment.

2.3. WAVE model

The WAVE model was used to analyze the experiment and simulate impacts for uncertain future scenarios (Vanclooster et al., 1996). WAVE describes 1-D water, heat and mass transport in the soil-crop continuum. WAVE numerically solves the 1-D isothermal flow equation for partially saturated rigid porous media that is represented by the Richards equation. The model uses the water-retention curve described by van Genuchten (1980) and the unsaturated hydraulic conductivity model described by Mualem (1976). More details can be found in Gabriel et al. (2012b). A MATLAB (MathWorks Inc., Natick, MA, USA) version of the model was implemented, including subroutines from SWATNIT (Simulating WATER and NITrogen; Vereecken et al., 1991) and LEACHN (Leaching Estimation and Chemistry model. Nitrogen; Wagenet and Hutson, 1989), for water, solute, heat and N transport. Moreover, two new subroutines were included for improving the crop component of the model. The first new subroutine simulates crop growth using a generic crop growth simulator. The subroutine allows estimating crop growth, together with its nitrogen content. This crop subroutine was based principally on the WOFOST crop model (Diepen et al., 1986) and the previous SUCROS code (Spitters et al., 1988; Van Keulen et al., 1982). The atmospheric N_2 fixation by legume crops was considered in the subroutine as a fixed factor of 33% of the total N content in the vetch, that could increase if the N became a limitation, based

on the data obtained by Gabriel and Quemada (2011). Required weather data are daily temperature and PAR (assumed to be equal to 50% of the total radiation). PAR is converted into biomass increase using the light interception capacity and considering energy for maintaining plant organs. The biomass development rate is translated into leaf area index (LAI) development rate using plant stage partitioning coefficients. The duration of the phenological phase is calculated using a crop phenological thermal time that equals the cumulative phenological temperature above a given threshold value and below a maximum upper limit. Crop growth is also affected by temperature, water and nitrogen stress in the root zone of the crop and crop senescence. Root development considers a triangular root density profile distribution. The rooting depth is also based on a thermal time until a maximum rooting depth is reached. Finally, the crop height is calculated directly in terms of thermal time.

The second new subroutine included is an evapotranspiration (ET) subroutine that calculates the potential evapotranspiration described by Allen et al. (1998) based on the dual coefficient. The dual coefficient approach uses two coefficients that multiply the reference evapotranspiration to divide it into evaporation and transpiration. In the surface covered by plants, only transpiration occurs, and in the surface not covered, only the evaporation process occurs. The ET subroutine allows calculation for three conditions: i) there are no crops, ii) there are crops growing and transpiring, and iii) there are dead crops, which do not transpire but reduce evaporation, covering the soil. For the first option, the crop coefficient, the soil coverage and the crop height are fixed at 0, and the evaporation coefficient is set equal to 1 as suggested by the FAO guideline for bare soils. When the crops are transpiring, evaporation is estimated in the same way but is corrected by the soil fraction not covered by crops. In our study, soil cover was obtained from the LAI simulated by the crop subroutine and corrected by Ramírez-García et al. (2012). The basic crop coefficient followed the plateau model described by Allen et al. (1998). We used an initial value of soil coverage less than 10%, followed by a constant slope until a plateau with the maximum value of more than 80% soil coverage was reached. Subsequently, a constant decrease followed until a final value at harvest time. These coefficients were also corrected by the wind speed and the air humidity deficit. When there are residues, which do not transpire, the transpiration coefficient is set equal to 0, and the evaporation coefficient is calculated as if there was no crop but corrected by the surface not covered by the crop. Both crop and ET subroutines allow simulating potential water and N uptake by roots from different plants. The water and N uptake rates are further corrected in terms of water and nutrient availabilities in the root system.

2.4. WAVE calibration

A stepped calibration approach was implemented, providing parameters for the different modules using different parts of the available data set. The soil hydraulic parameters were previously calibrated and validated for this experiment by Gabriel et al. (2013) using data from the fallow period between October 2006 and April 2007. In this first step, no plant interactions were considered. The soil hydraulic parameters were identified for four homogeneous layers defined (0–20, 20–40, 40–80 and 80–120 cm depth) by coupling WAVE to the Shuffled Complex Evolution Metropolis algorithm for Optimization Uncertainty Assessment (SCEM-UA, Vrugt et al., 2003). This global optimization algorithm is a Bayesian inversion method based on the Markov chain Monte Carlo method (Gilks et al., 1998). The algorithm uses the Metropolis Hastings Strategy (Metropolis et al., 1953) for evolving the population of plausible parameters in the optimization, toward the most likely parameter set. The method also allows quantifying the posterior probability distribution of the parameter, conditioned to available observations. The fit of the simulations to the observed data was evaluated by the coefficient of efficiency (C_{eff} ; Nash and Sutcliffe, 1970) and the

root mean squared error (RMSE), as suggested by Ritter and Muñoz-Carpena (2013).

In a second step, the crop parameters (barley and vetch) were manually calibrated. First, the simulated time course of crop phenology was adjusted to the observed phenology in the field. Second, growth parameters were adjusted to the observed soil coverage, aerial biomass, root depth and root biomass in the field. Finally, the N uptake parameters were also adjusted to the observed N uptake.

The soil nitrogen balance parameters were calibrated in a third step. The calibration consisted again of an automatic inverse calibration with the SCEM-UA approach. Optimal N fate parameters for each soil layer were matched toward the observed NO_3^- and NH_4^+ content for each soil layer. The data set used for the calibration of the N fate parameter calibration was the 2008/09 cover crop/maize season data set, because it included contrasting dry and wet conditions during the same period. Additionally, initial Nmin during that period was more representative of equilibrium conditions than the first year. In this latter case, Nmin was much higher. In total, there were 21 parameters calibrated, ten of them adjusted for each of the four homogeneous layers during the water calibration.

2.5. WAVE validation

The validation was divided into two main parts, matching both with the 4- and 2-year data set. Validation of the 4-year experiment consisted of a comparison of the simulated versus observed crop properties (aerial biomass, N uptake, soil coverage and root depth), soil water properties (soil water content at the four different layers) and soil nitrogen properties (NO_3^- and NH_4^+ content for each soil layer at each cover crop termination date and NO_3^- and NH_4^+ concentration in percolated water from the suction cups) for the years that were not used for calibration. In the case of the suction cups, the entire experimental period was used for validation because no data were used for calibration. The model simulations were also validated with the entire 2-year experimental data set. The validation consisted, again, of a comparison of the simulated versus observed soil and crop data. However, the simulated crop outputs were evaluated for the two different cover crop termination dates. The NO_3^- and NH_4^+ content for each soil layer was evaluated at a hypothetical sowing date (April 17th), after the second cover crop termination date.

2.6. Scenario analysis

The calibrated and validated model was subsequently used in advanced scenario analysis. The simulations consisted of a fallow and mixed cover crop, like the one studied in the 2-year experiment, sown on October 10th, combined with four different termination dates (March 1st and 15th and April 1st and 14th), with two different hypothetical cash crop planting dates (HPD, April 15th and May 1st), and four soil autumn conditions at cover crop sowing each year were considered, combining low and high rate of SWC and Nmin ($\text{SWC}_0/\text{Nmin}_0$). Therefore, the WAVE model was used for a total of 40 agronomical scenarios (Table 1). Each year, the simulation started at the cover crop sowing and stopped at the HPD. Six outputs were studied: cumulated cover crop biomass, water transpiration, water

percolated and nitrate leached during the cover crop period, and SWC and Nmin in the sowing bed (0–20 cm) at the cash crop sowing date.

For simulations under the current climate, the 40 agronomical scenarios were run for a 30-year baseline observed time series (1979–2009) from the AEMET (State Meteorological Agency of Spain) meteorological station at 30.98 km away from the experimental site. The time series implemented used a daily time step for global solar radiation, minimum and maximum temperature, precipitation, wind speed and relative humidity. Once all simulations were performed, the @RISK software (Palisade Corp., Newfield, NY, USA) was used to generate probability distribution curves for each output studied and for each of the 40 agronomical scenarios. Each output was fitted with different models, and the best was selected based on the minimum χ^2 criterion.

For simulations under the future climate, the baseline weather data were perturbed. To create the perturbed dataset, temperature and precipitation baseline values from the observed data series were systematically modified using a “change factor” approach (Fronzek et al., 2010). Observed daily maximum and minimum temperatures were modified between -1°C and $+7^\circ\text{C}$ at 1°C intervals, while daily precipitation was modified between -40% and $+30\%$ at 10% intervals, resulting in 72 combinations of temperature and precipitation changes. The ranges of temperature and precipitation changes were set wide enough to encompass the changes projected by climate models from CMIP5 ensemble (IPCC, 2013) and the probabilistic dataset of projections by Harris et al. (2010) for the location under study by the mid-21st century.

This scheme resulted in 72 30-year perturbed weather time series that represent possible future climate conditions for which each of the 40 agronomical scenarios were run with the validated WAVE model. To analyze the results, WAVE outputs were plotted using impact response surfaces interpolating model response to the changes in temperature and precipitation as contour lines using the statistical software package R ver. 3.2.3 (R Core Team, 2015).

3. Results

3.1. WAVE calibration and validation

The results of the model calibration and validation are summarized in Table 2. The best adjustments were obtained for the SWC, ranging the RMSE between 5.4 and 8.3 mm along the 1.2 m depth profile, while the field observed SE was between 15.3 and 25.4 mm. The simulated plant outputs (aerial biomass, root biomass, N uptake and soil coverage) resulted in RMSE similar to the natural variability observed in the field during the calibration and the validation periods, suggesting that it would be difficult to reduce under these conditions. The simulated soil mineral N (as NO_3^- and as NH_4^+) also resulted in RMSE similar to the actual deviation observed in the field. Lastly, the Nmin concentration simulated in the percolation water, in this case, measured only during the 4-year experiment, was smaller (16.8 mg N L^{-1}) than the actual SE observed between suction cups (34.1 mg N L^{-1}).

3.2. WAVE application under actual conditions

During the 30-years baseline period, precipitation during the cover crop season ranged from 70 to 400 mm. The distribution adjusted to a

Table 1
Cover crop-fallow agronomical scenarios simulated, used for current and climate change conditions, combining 2 different initial soil mineral N content (Nmin_0), 2 different initial soil water content (SWC_0), 2 hypothetical planting dates (HPD) for the following cash crop and 4 cover crop termination dates (TD).

Cover crop presence	SWC_0	Nmin_0	Hypothetical planting date	Termination date	Treatments
-Fallow	-High	-High	-HPD1 (April 15th)		8
	-Low	-Low	-HPD2 (May 1st)		
-Cover crop	-High	-High	-HPD1 (April 15th)	-TD1 (March 1st)	32
				-TD2 (March 15th)	
	-Low	-Low	-HPD2 (May 1st)	-TD3 (April 1st)	
				-TD4 (April 14th)	

Table 2

Coefficient of efficiency (C_{eff} ; dimensionless) and the root mean squared error (RMSE) obtained with the simulations compared with the standard error (SE) observed in the field measurements during the calibration and both validation periods.

		Daily SWC mm	Aerial biomass kg d.m. ha ⁻¹	Root biomass	N uptake kg N ha ⁻¹	Soil NO ₃ ⁻	Soil NH ₄ ⁺	Soil coverage %	Conc. Nmin mg N L ⁻¹
Calibration	C_{eff}	0.933	**	**	**	**	**	**	**
	RMSE	5.4	1997	658	13.1	34.1	4.2	13.3	u.v.
	Field SE	15.3	1057	545	14.1	47.9	4.3	14.1	u.v.
Validation 4-year	C_{eff}	0.893	**	**	**	**	**	**	**
	RMSE	8.3	1368	1030	52.0	57.8	2.3	13.4	16.8
	Field SE	25.4	1359	1322	26.5	56.5	3.1	17.6	34.1
Validation 2-year	C_{eff}	0.712	**	n.m.	**	**	**	**	n.m.
	RMSE	5.6	851	n.m.	62.4	45.8	2.1	16.7	n.m.
	Field SE	19.2	581	n.m.	30.4	20	1.5	11.4	n.m.

Abbreviations used: SWC (soil water content), Conc. Nmin (mineral N concentration in percolation water), d.m. (dry matter).

** (Not calculated), n.m. (not measured in the field), u.v. (used during validation).

Weibull function, with the median value of 250 mm. During the period between both HPD (mid-April to May 1st), the average rainfall was ~20 mm. The final cover crop biomass adjusted also to a Weibull function (Fig. 1). In this case, the final cover crop biomass was independent of the soil autumn conditions but increased approximately 1000–1500 kg ha⁻¹ every 15 days in spring. Therefore, from the earliest cover crop termination date (March 1st) to the latest (April 14th), biomass differed on average in ~4000 kg ha⁻¹. The cover crop biomass transpiration adjusted to a Gamma distribution function (Fig. 1) and it depended on the autumn SWC₀. Under low SWC₀ scenarios, lower transpiration values and a larger variability were observed (ranging from 5 to 125 mm with a median at 50). Under high SWC₀ scenarios, transpiration was on average ~20 mm larger, and the range observed started in 30 mm. As in the case of cover crop biomass, delaying the termination date led to higher transpiration, ~10 mm every 15 days, lower during the low rainfall years and lightly larger in the others.

Total percolation during the cover crop season was adjusted to a Gamma distribution function (Fig. 2). The transpiration, percolation water was dependent on the autumn SWC₀, but not on the Nmin₀. A high autumn SWC₀ favored percolation water in all treatments. Percolation rates increased on average 60 mm in the fallow treatment compared to the cover crop treatments. Meanwhile, in the low autumn

SWC₀ scenarios, percolation water was very low in all treatments and the fallow increment was more variable and smaller than 30 mm for 60% of the years, although this increase represented a doubling of the percolation water with respect to the cover crop treatment. The second HPD resulted in a 2–7 mm percolation water increase, and the cover crop treatment was more affected for the earliest termination date and under low autumn SWC₀.

Nitrate leaching was influenced by treatments but also by both SWC₀ and Nmin₀ autumn conditions (Fig. 3). In low autumn SWC₀, when percolation water was low, N leaching was also very low during the cover crop period. Under these conditions, cover crop treatment halves the leaching compared to the fallow treatments (80% of the years, N leaching is below 50 kg N ha⁻¹ in cover crop treatments and below 100 kg N ha⁻¹ in fallow if autumn Nmin₀ was low). If the autumn Nmin₀ was high, the differences in N leaching increased not only between cover crop treatments and fallow but also between HPDs (increasing, on average, by 25 and 20 kg N ha⁻¹ for fallow and cover crops, respectively). In this case, leaching below 50 kg N ha⁻¹ in cover crop treatments was obtained only for 60% of the years in the late termination date and 50% of the years in the early one. Additionally, leaching below 100 kg N ha⁻¹ is obtained in the fallow treatment between 50 and 55% of the years, depending on the HPD, with a higher risk of a very high amount of N leached for both cover crops and fallow. In high autumn SWC₀ scenarios, the differences between treatments

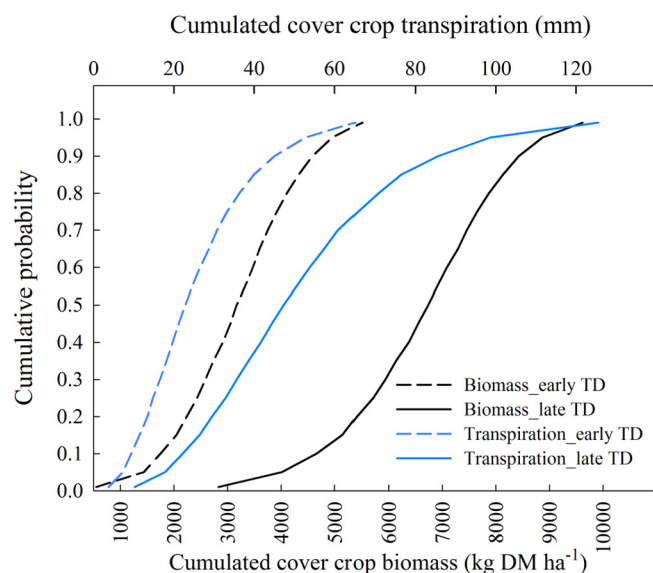


Fig. 1. Cover crop biomass (black lines) and transpiration (blue lines) cumulative probability for cover crop treatments terminated on March 1st (early TD) and on April 14th (late TD). Values correspond to the low SWC₀ and low Nmin₀ scenario. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

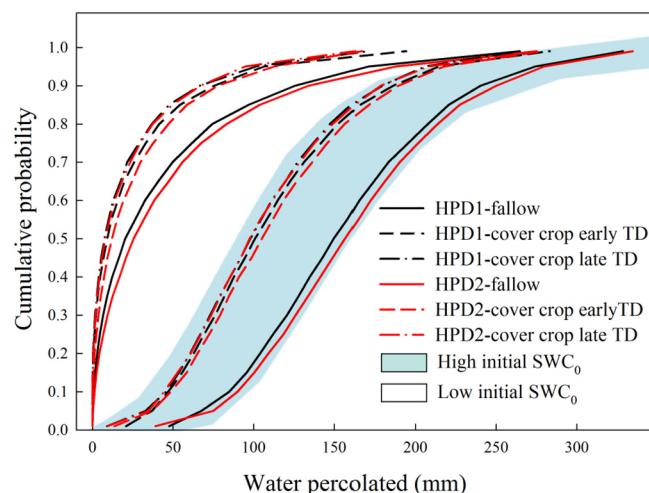


Fig. 2. Percolation cumulative probability for different agronomical treatments: fallow and cover crop with different termination dates (early TD, 1st March; late TD, 14th April), and with different hypothetical planting dates (HPD). Results in high autumn SWC₀ scenario are shaded in blue, while results in a low SWC₀ scenario are not shaded. Values correspond to the Nmin₀ scenario. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

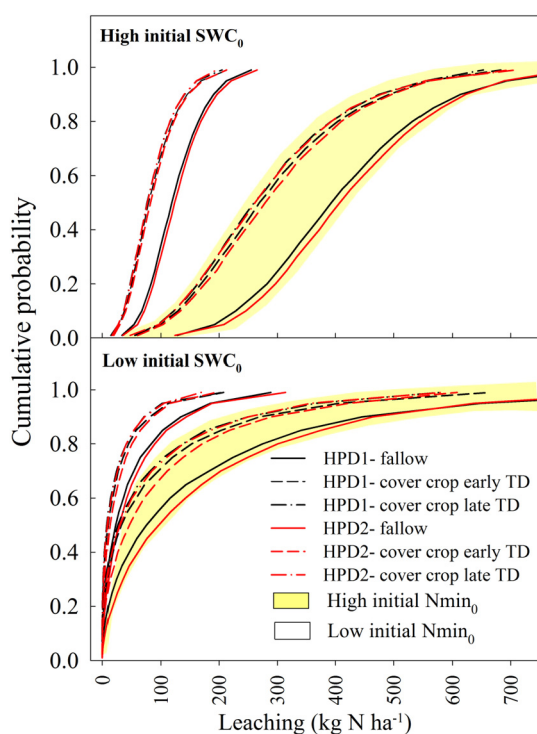


Fig. 3. Leaching cumulative probability for different agronomical treatments: fallow and cover crop with different termination dates (early TD, 1st March; late TD, 14th April), and with different hypothetical planting dates (HPD). Results for high and low autumn SWC_0 scenarios are found in the upper and lower graphs respectively; while results in high and low $Nmin_0$ scenarios are indicated with blue shading or without, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

remained more constant. When the autumn $Nmin_0$ was low, there was no difference between different termination date treatments, and the difference between cover crop and fallow treatment was $\sim 50 \text{ kg N ha}^{-1}$. The variation between years was very low, ranging for 80% of the years between 40 and 145 kg N ha^{-1} for the cover crop treatments, and between 70 and 200 kg N ha^{-1} for the fallow treatments. The HPD had a very low effect. When the autumn $Nmin_0$ was high, all differences increased. The N leaching of the earliest cover crop termination date treatment increased with 17 kg N ha^{-1} compared to the latest cover crop termination date treatment. The leaching of the fallow treatment increased with 150 kg N ha^{-1} with respect to the cover crop treatment. The leaching of the latest HPD treatment increased leaching with 20 kg N ha^{-1} . In this case, the range of leaching rates was larger, for the 80% of the years between 125 and 475 kg N ha^{-1} for the cover crop treatments and between 225 and 625 kg N ha^{-1} for the fallow treatment.

Soil water content at HPD adjusted to a Pearson5 distribution function (Fig. 4). The results were independent of the autumn soil conditions for the cover crop treatments, but autumn SWC_0 had some influence in the fallow treatment. The cover crop termination date had a great influence, with an SWC $0.10 \text{ m}^3 \text{ m}^{-3}$ lower for the latest termination date treatment compared to the earliest termination date treatment. This difference was partially reduced when HPD was delayed, refilling the soil with $0.02 \text{ m}^3 \text{ m}^{-3}$ of water for the earliest termination date treatment and with $0.04 \text{ m}^3 \text{ m}^{-3}$ for the latest termination date treatment. The fallow treatment exhibited an $\sim 0.05 \text{ m}^3 \text{ m}^{-3}$ higher SWC than the most humid cover crop treatment when the autumn SWC_0 was high but less than that when the SWC_0 was low. For 80% of the years, the SWC at HPD most competitive cover crop treatment ranged between 0.18 and $0.29 \text{ m}^3 \text{ m}^{-3}$, the less competitive between 0.27 and $0.43 \text{ m}^3 \text{ m}^{-3}$ and the fallow treatment between 0.33 and 0.45 when autumn SWC_0 was high and between 0.27 and $0.46 \text{ m}^3 \text{ m}^{-3}$ when it was low.

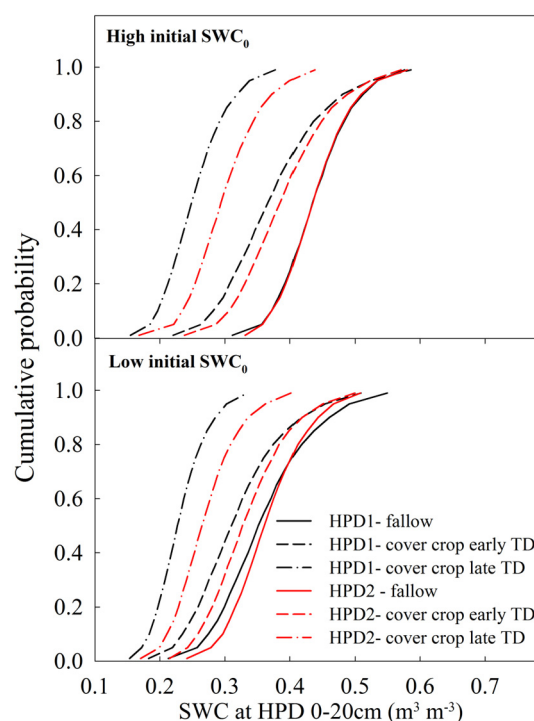


Fig. 4. Soil water content at the hypothetical planting date (HPD, 0–20 cm) cumulative probability for different agronomical treatments: fallow and cover crop with different termination dates (early TD, 1st March; late TD, 14th April), with different HPD. Results in high and low autumn SWC_0 scenarios are found in the upper and lower graph respectively. Both graphs refer to low $Nmin_0$ results.

The $Nmin$ content at HPD adjusted to an InvGauss distribution function (Fig. 5). The results were dependent on autumn $Nmin_0$ but not on SWC_0 . When the autumn $Nmin_0$ was low, the differences between

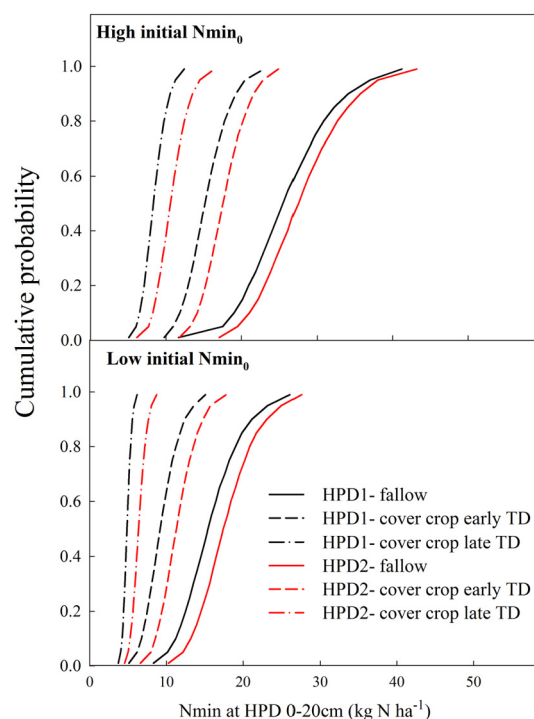


Fig. 5. $Nmin$ at the hypothetical planting date (HPD, 0–20 cm) cumulative probability for different agronomical treatments: fallow and cover crop with different termination dates (early TD, 1st March; late TD, 14th April), and with different HPD. Results in high and low autumn $Nmin_0$ scenarios are found in the upper and lower graph respectively. Both graphs refer to low autumn SWC_0 results.

treatments and values at different years were both constant. The latest HPD treatment increased N_{min} with 2.5 kg N ha^{-1} and the termination date in 8 kg N ha^{-1} . For 80% of the years, the most competitive cover crop treatment resulted in N_{min} content between 13 and 19 kg N ha^{-1} , the less competitive treatment between 22 and 29 kg N ha^{-1} and the fallow treatment at the latest HPD between 31 and 45 kg N ha^{-1} . When the autumn N_{min_0} was high, the differences increased between years, but not between HPD treatments or cover crop termination date treatments. In this case, the ranges for the 80% of the years were between 24 and 52 kg N ha^{-1} for the most competitive cover crop treatment, 36 and 59 for the less competitive treatment, and between 48 and 86 for the fallow treatment at the latest HPD.

3.3. WAVE application under climate change conditions

The cover crop final biomass under future climate conditions increased with cover crop cycle temperature, showing that cover crop biomass was limited mainly by temperature. An increase from 0 to $+2^\circ\text{C}$ almost doubled the biomass: therefore, a cover crop with the earliest termination date could pass from 3000 kg ha^{-1} of biomass produced to 6000 kg ha^{-1} , or a late-terminated cover crop from 6500 to $11,500 \text{ kg ha}^{-1}$. Cover crop transpiration was also influenced mainly by temperature perturbation, but it also started to show some small influence by precipitation perturbations. As in the case of the biomass, when water is not a limitation (because higher SWC_0 , no precipitation reduction or earlier cover crop termination), the transpiration increment with the temperature is linear and equivalent to $10 \text{ mm } ^\circ\text{C}^{-1}$ on average. However, as soon as water starts to be a limiting factor, transpiration rate decreases slightly.

The percolation water simulated for the fallow treatment was mainly affected by the precipitation, reducing $\sim 20 \text{ mm}$ percolation every 10% of rainfall reduction (Fig. 6). However, a hypothetical 6°C temperature increase was only able to reduce 10 mm percolation because evaporation increased. However, the percolation water in the cover crop treatments was affected in a similar way by both precipitation and temperature. The percolation reduction was approximately 10–15 mm for every 10% of rainfall reduction, while it was between 5 and 10 mm

for every 1°C of temperature increase, depending on the absolute value of the baseline percolation water rate for each initial condition simulated. Like the percolation water, the nitrate leaching in the fallow treatments was mostly influenced by precipitation, whereas in the cover crop treatments, both precipitation and temperature affected leaching, although the precipitation influence was stronger (Fig. 7). Differences between treatments were highly dependent on the nitrate leaching baseline, and then on the autumn SWC_0 and N_{min_0} and the cover crop treatment. However, cover crop treatments always reduced more nitrate leaching than the fallow treatment when the temperature increased, independent of the precipitation perturbation.

The soil initial conditions at HPD for both SWC and N_{min} were affected by both temperature and precipitation changes. The SWC in the fallow treatment was mostly affected by the precipitation changes, followed by autumn SWC_0 and HPD, but almost not by temperature changes (Fig. 8). However, the cover crop treatments were also highly affected by temperature changes, producing a higher potential competition for water with the next cash crop than in the fallow treatment under moderate temperature (up to ca. $3\text{--}4^\circ\text{C}$) and all precipitation perturbations. For instance, when temperature increased 2°C and precipitation decreased 10%, the fallow treatment always accumulated more SWC than $0.34 \text{ m}^3 \text{ m}^{-3}$ in an average year, whereas a cover crop accumulated water between 0.28 and $0.31 \text{ m}^3 \text{ m}^{-3}$ if terminated early and between 0.22 and $0.25 \text{ m}^3 \text{ m}^{-3}$ in case of late termination. As occurred under actual conditions, when HPD was delayed the soil was refilled with $0.01 \text{ m}^3 \text{ m}^{-3}$ of water for the earliest TD treatment and with $0.03 \text{ m}^3 \text{ m}^{-3}$ for the latest TD treatment. Inversely to SWC , the soil N_{min} at HPD was more affected by temperature and precipitation changes in the fallow treatment than in the cover crop treatments (Fig. 9). While the temperature increases and precipitation decreases, the fallow treatments tend to increase available N_{min} because of the higher mineralization of organic matter (due to temperature increase) and nitrate leaching reduction (i.e., $\sim 5 \text{ kg N ha}^{-1}$ every 10% of precipitation reduction and 2°C increase). However, almost no variation with respect to the cover crop scenario baseline was observed. This effect tended to increase differences in the initial soil conditions between fallow and cover crop treatments, again producing a higher potential

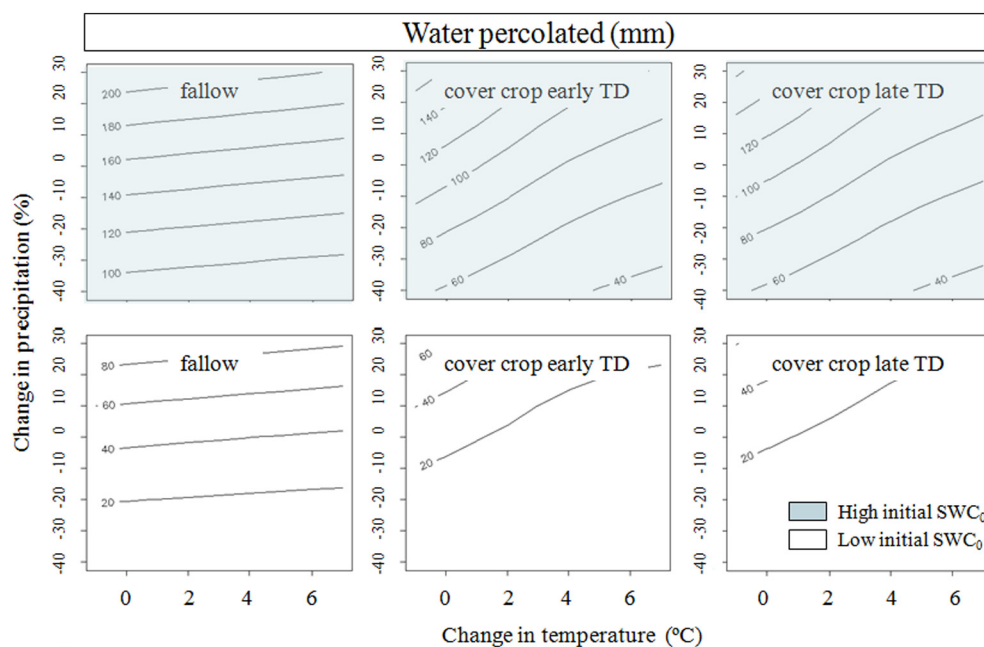


Fig. 6. Water percolated (mm) response to changes in temperatures (x-axis) and precipitation (y-axis) relative to the baseline (1979–2009) for the agronomic treatments: fallow, cover crop terminated on March 1st (early TD) and terminated on April 14th (late TD). Upper graphs blue shaded correspond to high autumn SWC_0 scenarios, while lower graphs without shading correspond to low SWC_0 scenarios. All graphs refer to low autumn N_{min_0} results and to the early hypothetical planting date (HPD1, 15th April). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

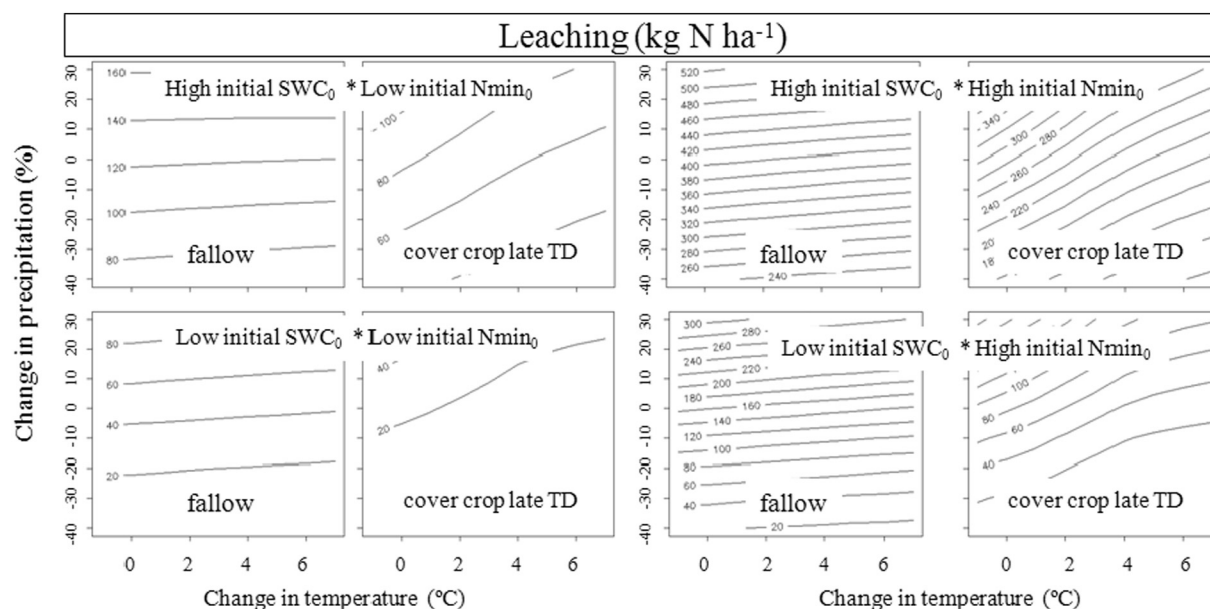


Fig. 7. Nitrate leaching (kg N ha^{-1}) response to changes in temperatures (x-axis) and precipitation (y-axis) relative to the baseline (1979–2009) for the fallow treatment and for the cover crop treatment terminated on April 14th (late TD), in the four combinations of autumn SWC_0 and Nmin_0 scenarios. All graphs refer to the early hypothetical planting date (HPD1, 15th April).

competition for N with the next cash crop under temperature and precipitation perturbation representative of future climate. However, this competition is more important at HPD, because subsequent mineralization of the cover crop residues can diminish this effect along the cash crop cycle.

4. Discussion

The inverse calibration of the hydraulic, crop and N cycle parameters of the physically based water and nutrient balance model WAVE provided a good estimation of the crop growth, soil water and soil mineral N processes of a multi-year cash crop-cover crop rotation experiment under Mediterranean conditions. Moreover, the results of the validation with an independent dataset resulted in adjustment to the observed data similar to the calibration. The modeling errors of the observed system properties were usually smaller than the observed field variability, reinforcing the efficiency of the model for simulating the behavior of this cropping system. In the case of the water content, the relative RMSE observed was 2.3% for the calibration period and 3.6 and 2.6% for the validation with the 4- and 2-year experiments, respectively, much lower than the 10% defined as acceptable for water balance by Coucheney et al. (2015). This modeling performance may be due to the comprehensive physical modeling structure, which generally is more versatile than the classic tipping-bucket approach (Soldevilla-Martínez et al., 2014). It was also the result of the global inverse calibration that allows parameterizing complex non-linear system models based on high time resolution field data in an efficient way, as suggested previously by Ritter et al. (2003). The crop relative RMSE was, on average, 26.1% and 34.9% for the aerial and root biomass, respectively. These values were again close to or lower than the reference 35% presented by Coucheney et al. (2015) as acceptable when evaluating the crop component of the STICS model. However, further research is needed in order to confirm the correct interactions between the cover crop mixture components. The N balance components presented an average relative RMSE equal to 30.8%, 30.3% and 40.6% for crop N content, soil Nmin and nitrate concentration in the percolation water. This is relatively high but still like the values obtained by Payet et al. (2009) using the Fortran version of the WAVE model. Again, these values were lower than the proposed values by Coucheney et al. (2015), 33% for N components and 49% for nitrate leaching. Although actual nitrate leaching has

not been directly measured, N concentration in the percolation water could be considered in this case the main error source as the water balance error was very small. It is remarkable to notice that these calibration and validation adjustments were achieved under very different weather conditions, as they were already pointed by Gabriel et al. (2012b) from 2006 to 2010 for the first experiment and by Alonso-Ayuso et al. (2014) from 2011 to 2103 for the second one.

The application of a validated model to the 40 agronomical scenarios and the 30-year baseline weather time series confirmed the importance of the termination date of the cover crop to maximize cover crop benefits (Alonso-Ayuso et al., 2014). Moreover, this process increased the representativity of the results under high temporal variability. Significant differences were found in cover crop outputs (cumulated biomass and transpiration), percolation water and leaching, and in both SWC and Nmin at HPD, suggesting an increase in the competition with the following cash crop. As was observed in other studies (Alonso-Ayuso et al., 2014; Sainju and Singh, 2001), delaying the termination date in spring led to a higher simulated aboveground biomass accumulation, as the cover crop had more time for growing. Differences in biomass simulation for cover crops for different termination date scenarios were like those observed in other regions (Clark et al., 1997; Lawson et al., 2015; Waggoner, 1989). The simulated produced biomass was independent of soil autumn conditions (in terms of water and N). This effect is suggesting that the mixture of cover crops used in this experiment (barley-vetch) can be established under a broad range of circumstances, even in soils that have been previously depleted or with very low SWC. Grasses have already been reported as more tolerant to drought conditions in semiarid regions (Bilbro, 1991; Gabriel et al., 2016; Unger and Vigil, 1998). However, the vetch is a facultative N_2 fixer, varying the amount of N fixed depending on the available Nmin in the soil (Gabriel and Quemada, 2011). These two properties together make the mixture more plastic to adverse conditions than using these crops separately (Tribouillois et al., 2016).

The leaching of nitrate and other pollutants is one of the most important issues when cropping system environmental sustainability is studied. However, leaching is very difficult to measure directly in the field (Webster et al., 1993). Then, modeling is an interesting approach to compare the impact of different forms of cropping management on leaching. In this case, the WAVE model allowed quantifying the nitrate leached for the different cover cropping management techniques. The

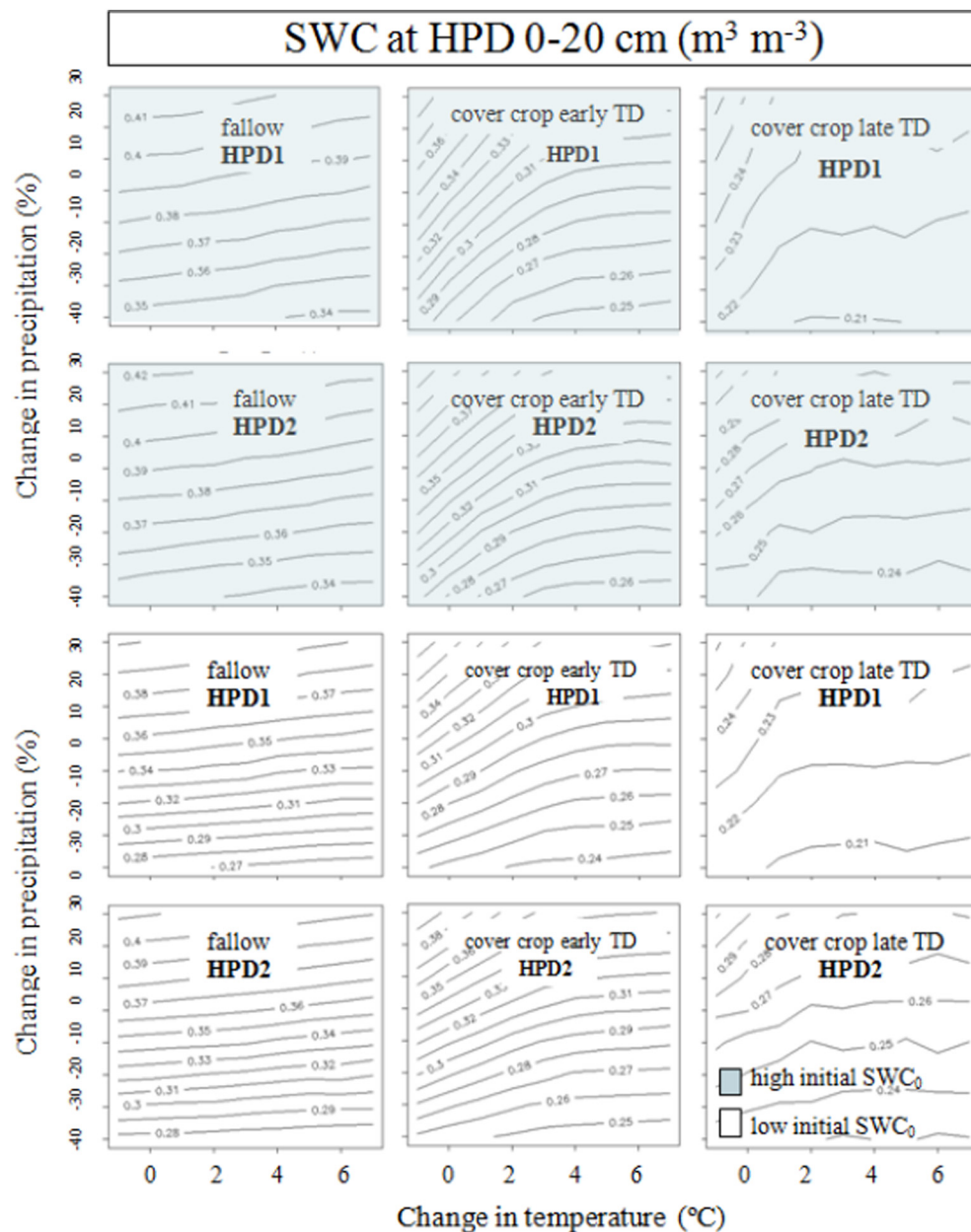


Fig. 8. Soil water content at the HPD (in 0–20 cm, $\text{m}^3 \text{m}^{-3}$) response to changes in temperatures (x-axis) and precipitation (y-axis) relative to the baseline (1979–2009) for the agronomic treatments: fallow, cover crop terminated on March 1st (early TD) and terminated on April 14th (late TD), with different HPD. Upper graphs blue shaded correspond to high autumn SWC_0 scenarios, while lower graphs without shading correspond to low SWC_0 scenarios. All graphs refer to low autumn Nmin_0 results. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

modeling setup also allowed quantifying the associated interannual leaching variability. Cover crop treatments always reduced percolation of water and nitrate leaching compared to fallow treatment, which is consistent with previous studies (Dinnes et al., 2002; Strock et al., 2004; Thorup-Kristensen et al., 2003). However, the simulated reduction was larger, as the soil or/and the climatic conditions favored large leaching periods. This leaching appeared to be very dependent on soil autumn condition as values moved in wide ranges depending on the autumn soil N and water content. The scenario analysis also suggested that high nitrate leaching during the intercropping period could occur, in particular when two or more adverse situations were combined, especially high Nmin_0 and water in autumn with high precipitation in winter. This simulated synergic effect was like the effect already reported for semiarid conditions by Ruiz-Ramos et al. (2011). In their study, Nmin accumulates during the dry periods and leaches out of the soil profile when an unusually heavy rainy season occurs. The cover crop

effect on the nitrate leaching reduction must be produced mostly during the first months of the cover cropping period, because early termination dates and late HPD had a very small effect on the final nitrate leaching. This effect is very interesting because some authors suggested delaying cover crop termination to improve nutrient recycling (Lawson et al., 2015; Thorup-Kristensen and Dresbøll, 2010). A delay in the cover crop termination allows more time for the cover crop to deplete water and nutrients from the soil profile and hence reduces water and nutrient leaching. An early HPD also reduces losses, as in the second part of April the percolation water could increase due to rainfall events (~20 mm), and nutrients could be lost by leaching if the cash crop is not present or it is still small (Vázquez et al., 2006). If the period between cover crop termination and HPD is very long, the mulch at the surface will decompose and release additional nutrients that will be prone to losses when heavy precipitation events occur. However, if the effect of the termination date on nitrate leaching is small, early

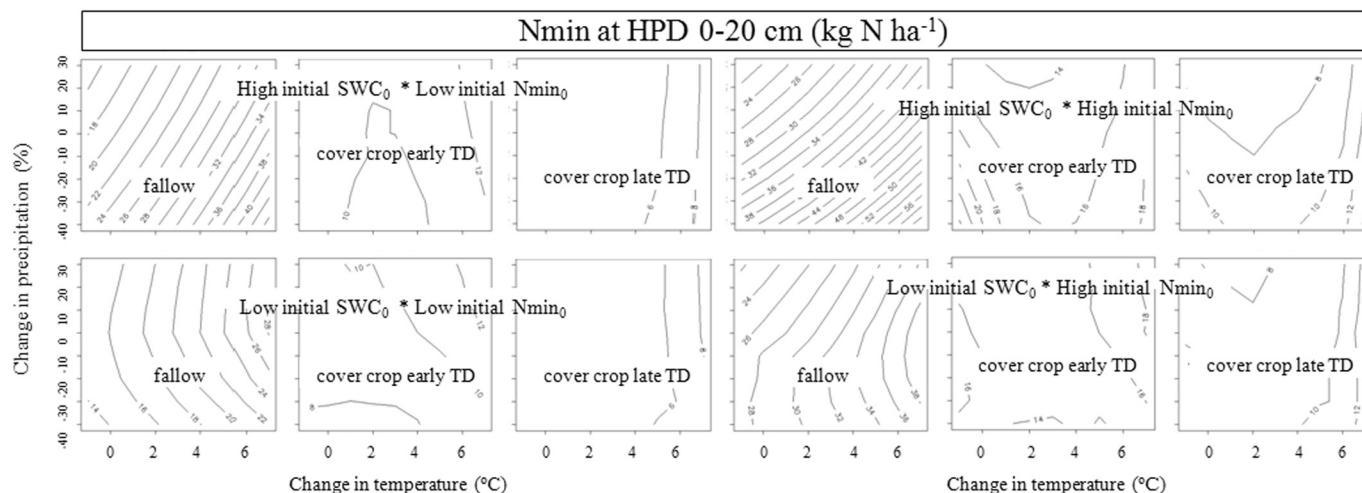


Fig. 9. Soil Nmin at the HPD (in 0–20 cm, kg N ha⁻¹) response to changes in temperatures (x-axis) and precipitation (y-axis) relative to the baseline (1979–2009) for the agronomic treatments: fallow, cover crop terminated on March 1st (early TD) and terminated on April 14th (late TD), in the four combinations of autumn SWC₀ and Nmin₀ scenarios. All graphs refer to the early hypothetical planting date (HPD1, 15th April).

cover crop termination could be a valid option. Indeed, under these conditions, farmers have more time for performing the required soil management, also allowing crop residues to mineralize and the soil to reduce water and nutrient competition (Alonso-Ayuso et al., 2014).

Suspected competition of cover crop for water and nitrogen with the subsequent cash crop has limited the appropriation of cover cropping by farmers (Unger and Vigil, 1998). In this study, the water and Nmin content in the soil upper layer at the cash crop HPD showed that this could be an actual concern in some situations. When delaying the HPD and providing early termination of cover crops, competition was at its minimum. The water competition in the upper 20 cm could easily be solved if irrigation is available (and under semiarid conditions, maize is usually irrigated) with the application of 35 mm under the most unfavorable conditions, as previously described McGuire et al. (1998), Mitchell et al. (1999) or Krueger et al. (2011). However, when the time between the cover crop termination and HPD increases, system performance will be reduced, in particular with important rainfall events. In addition, the cover crop mulch produced can help to reduce water losses, preventing direct evaporation and increasing water availability for the cash crop after HPD (Clark et al., 1997). The differences in Nmin were also reduced, increasing the time between cover crop termination and the HPD. Similar competition was also observed by Thorup-Kristensen (1994). However, only terminating the cover crop very late led to less than 10 kg N ha⁻¹ of total soil Nmin on average in the upper 20 cm, and then presenting an actual limitation to the subsequent cash crop before the first dressing fertilization. Moreover, authors such as Thorup-Kristensen et al. (2003) and Gabriel and Quemada (2011) affirmed that there is a further effect of N recycling, because the N depleted from the entire profile is subsequently released into the top layers due to the residue mineralization, not reflected in these simulations because they stopped at HPD. Moreover, attention should be paid to the high Nmin levels in the fallow treatments, because this situation could lead to a leachate risk during the first stages of the cash crop, as suggested by Vázquez et al. (2006).

There are considerable uncertainties associated with the cover crop impact assessments under climate change. The first one comes from the climate projections themselves. The large ranges of precipitation and temperature changes used in this study were inferred from available climate models and illustrate the high uncertainties of the climate change signal in this Mediterranean environment. To handle this uncertainty, the use of impact response surfaces has proven to be an efficient tool to analyze numerous plausible climate and agronomical scenarios (Ruiz-Ramos et al., 2016). A second main uncertainty source comes from the scarcity of experimental and modeling studies dealing with

cover crops under climate change conditions. Based on the results obtained in this study, we conclude that cover crops tend to grow more and faster, mostly because of increasing temperature through a period where temperature is the most limiting factor. These results correspond with the results observed by Mínguez et al. (2007), Ruiz-Ramos et al. (2011) or Pirttioja et al. (2015) for the same winter period under semi-arid conditions for wheat. This possible biomass increase also affects both nitrate leaching and preemptive competition with the subsequent cash crop, but it could also improve the weed suppression capacity and the C sequestration (Pardo et al., 2017). With respect to the effect on nitrate leaching and preemptive competition, the simulated climatic change scenarios tended, in general, to increase the differences between the cover crop and fallow treatment. The scenarios with increased temperature produced an increment in the N mineralization for all treatments. The additional N could accumulate in the cover crop biomass, resulting in almost no effect in Nmin at HPD in a cover crop treatment. In contrast, Nmin tends to accumulate in the soil profile in a fallow treatment if the precipitation is reduced or to leach if the precipitation increases. In both cases, Nmin availability after the cover crops was not reduced. Therefore, actual competition for N with the subsequent cash crop was not so important for most of the management scenarios. The increased mineralization in the fallow treatment makes it more prone to cause environmental pollution under climatic change scenarios. Such an increased pollution risk will be higher when the temperature rises. A cautionary note should, however, be added. The drainage reduction by cover crops could result in possible salt accumulation, which should be controlled (Gabriel et al., 2012a). Soil water content at HPD was also affected in the climate change scenarios. Differences between fallow and cover crop treatments for these scenarios only increase when the temperature increases. Indeed, precipitation variation equally affects fallow and cover crop treatments. Therefore, under different climate change scenarios, fallow tends to increase preemptive competition with the subsequent cash crop and to increase nitrate leaching risk, while cover crops tend to be more resilient, maintaining the preemptive competition levels and reducing nitrate leaching with respect to the current situation. Therefore, the use of cover crops was confirmed as a meaningful strategy to climate change adaptation (Kaye and Quemada, 2017).

5. Conclusions

Including cover crops in the irrigated system rotation is an efficient technique for reducing nitrate leaching. However, there is a potential risk of preemptive competition with the following cash crop for water

and N that depends mainly on the termination date. The results obtained in this study, based on an accurate calibration and validation with field experiments of the water and nutrient balance model WAVE, allowed the analysis of several agronomical scenarios that would be unaffordable under field conditions, in terms of time and resources. These results show that earlier termination dates can reduce N and water competition with the following cash crop, without increasing nitrate leaching and conserving their ecosystem services. However, under climate change conditions, including cover crops in the rotation proved to be a useful technique to reduce nitrate leaching with respect to fallow, increasing their ecosystem services. In addition, the cover crop mulch reduces evaporation losses, preserving soil water during the irrigated period and increasing the sustainability of the system.

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