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Cover crops reduce drainage but not always soil water content due to interactions between rainfall distribution and management

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1. Introduction

Intensive agriculture has reached a critical point, particularly in Europe and temperate climate zones. Conventional agriculture is increasingly shown to be responsible for multiple problems, such as stagnating yields, a decrease in soil fertility, pollution of groundwater and rivers, and soil erosion. Agriculture must adapt in response to climate change, which is causing more droughts, less water availability, and more extreme climatic events (IPCC, 2013). Therefore, scientists, farmers and policy makers urgently need to find more sustainable and resilient cropping and farming systems. The use of cover crops could help cropping systems become more agroecological and diversified. Cover crops are sown after one cash crop is harvested and terminated before the next one is sown. Their residues are retained as a mulch or incorporated into the soil by plowing or shallow tillage, such as disking. Cover crops provide a wide range of ecosystem services, including reducing nitrate leaching (Tonitto et al., 2006); providing a "green manure" effect (Tosti et al., 2014; Tribouillois et al., 2015); improving physical properties of soil that reduce erosion or compaction (Chen and Weil, 2010; Ryder and Fares, 2008); decreasing greenhouse gas emissions; increasing carbon (C) storage in the soil (Poeplau and Don, 2015; Tribouillois et al., 2018a); and controlling pests, diseases, and weeds (Couëdel et al., 2018a; Haramoto and Gallandt, 2005; Schipanski et al., 2014). Using cover crops could also help mitigate and adapt to climate change (Kaye and Quemada, 2017). Tribouillois et al. (2018b) demonstrated the effective mitigating influence of cover crops and highlighted the challenge of finding a good compromise between certain ecosystem services they provide and the decrease in groundwater recharge they cause by increasing evapotranspiration of cropping systems.

Cover crops influence the soil water balance and water fluxes. They reduce water drainage in temperate climates (Meyer et al., 2019) and increase transpiration by increasing leaf cover transpiration and decreasing soil evaporation (Nielsen et al., 2015b; Qi et al., 2011). When well established, they can also increase water infiltration and reduce runoff (Eshel et al., 2015; Yu et al., 2016). However, the importance of these processes depends on cover crop management, climate, and soil type. No consensus exists about the impact of cover crops on soil water availability for the next cash crop. Corak et al. (1991) and Restovich et al. (2012) reported less water available with cover crops compared to that with bare soil, while Chen et al. (2014) and Daigh et al. (2014) found no significant differences between these two treatments at sowing of the next crop. Several studies reported more water in the topsoil (0-20 cm depth) (Blanco-Canqui et al., 2011; Wells et al., 2014). Likewise, no consensus exists about the impact of management of cover crop residues after cover crops are terminated. Several studies reported an increase in soil water content (SWC) up to 20 cm deep (Alliaume et al., 2014; Moschler et al., 1967; Stipešević and Kladivko, 2005). Williams and Weil (2004) observed no differences in soil moisture 20-50 cm deep between cover crop mulch and bare soil. Pedrosa De Azevedo et al. (1999) observed no significant difference in soil moisture between keeping cover crops alive during the fallow period and crushing them and leaving their residues as mulch. Kornecki et al. (2013) observed a small difference between these two treatments, with more soil moisture under the mulched cover crop.

It is also difficult to generalize the impact of cover crops on water balance because studies are performed in different contexts of fallow periods (e.g. August-November vs. October-April), climate conditions, and cover crop management. In some studies, cover crops are terminated in late winter or early spring, while in others they are terminated the day before sowing the next cash crop, especially when herbicide termination is used. These differences are crucial to understanding cover crop impacts, since multiple processes, of variable intensity, interact in these dynamics. Thus, spring rainfall can recharge the soil and mask differences in SWC and in the topsoil (seedbed of the next cash crop), even though water fluxes (e.g. drainage, evapotranspiration) flow simultaneously. Dynamic soil-crop models can be useful tools to estimate water fluxes that are difficult to measure in field experiments, such as drainage, evaporation, and transpiration, and can do so accurately over long periods. These models also can simulate a wide range of cover crop management practices under several soil and climate conditions and extrapolate results of field experiments that are expensive, time consuming, and rare (Bergez et al., 2010).

The goal of our study was to understand and quantify impacts of cover crops and their management on water flux dynamics (e.g. soil evaporation, plant transpiration, drainage) and balance at the crop rotation scale. Two components of the water balance were a particular focus of analysis: (1) drainage, which governs groundwater recharge, and (2) water availability for the next cash crop, which determines the risk of water deficit for crop emergence and early growth. We combined a two-year field experiment with simulation modeling to address this issue. The field experiment was performed to analyze impacts of cover crop management on dynamics of SWC and cover crop biomass. This field experiment was supplemented with a modeling approach using the STICS soil-crop model to understand and quantify the water flux dynamics (drainage, evaporation, and transpiration) not measured during the experiment.

2. Materials and methods

2.1 Methodological approach

To determine the impact of various cover crop management practices on soil water balance during the fallow period and soil water availability for the next spring/summer cash crop, the following methodological approach was used:

1. A two-year field experiment was performed to quantify the impact of three cover crop management practices on SWC in multiple soil layers during the fallow period compared to the SWC under bare soil, used as a control.
2. The dynamics of SWC and cover crop biomass measured in the experiment were used to calibrate the STICS soil-crop model for the mixed cover crop sown in the experiment and evaluate the model's ability to predict the experiment. The objective was to simulate soil and plant dynamics sufficiently well to obtain accurate simulations of water fluxes.
3. We assumed that if dynamics of SWC and crop biomass were simulated accurately, then those of water fluxes would also be simulated accurately. After verifying satisfactory agreement between model predictions and experimental observations, STICS was used to predict dynamics of soil evaporation, plant transpiration, and water drainage (processes not measured in the field) and the complete water balance for the two experimental years.
4. To place the weather during the two experimental years in the study site's interannual variability in climate, we used the calibrated STICS to simulate a 20-year climate series to better understand and generalize the impact of cover crop management on water fluxes and the complete water balance.

2.2 Case study site

2.2.1 Climate characteristics

A two-year experiment was performed from 2017-2018 and 2018-2019 (hereafter, "2017" and "2018", respectively) in southwestern France near Toulouse (43°31' N, 1°30' E). The site has a temperate climate corresponding to Cfb in the Köppen climate classification. Over the past two decades (1998-2018), the site's mean (± 1 standard deviation (SD)) annual temperature was 13.8 ± 0.5°C, annual potential evapotranspiration (PET) (Penman equation) was 962 ± 51 mm, and annual rainfall was 655 ± 105 mm. The weather conditions from cover crop sowing in July-August to termination in March-April differed during the two years of the experiment (Fig. 1). For 2017 and 2018, cumulative rainfall was 504 mm and 343 mm, and cumulative PET was 437 mm and 334 mm, respectively. In 2017, autumn was dry and winter and spring were rainy, with a high PET in the three months following the sowing of cover crops. Conversely, in 2018, autumn and early winter were rainy, with a low PET, and late winter and spring were dry. Cumulative temperature (calculated with base 0) from the day of cover crop sowing (31 July in 2017 and 28 August in 2018) until 9 April was 2920°C in 2017 and 2490°C in 2018.

(Figure 1)

2.2.2 Soil characteristics

The two-year experiment was performed at an Institut National de la Recherche Agronomique (INRA) experimental station on two field plots with similar soil characteristics: clay loam in 2017 and loam in 2018 (Table 1). Soil moisture at field capacity (FC) corresponded to the maximum observed during the experiment. Soil moisture at wilting point (WP) and bulk density (BD) were estimated based on soil texture classification and measurements at the experimental station (Jamagne et al. 1977; Tribouillois et al., 2016). Total available water capacity for plants (TAWC, SWC between FC and WP) was calculated down to 120 cm deep (the maximum root depth observed at this site; Tribouillois et al. (2016)). TAWC was nearly the same for the two plots: 152 and 164 mm in 2017 and 2018, respectively. The SWC at FC was 347 and 328 mm in 2017 and 2018, respectively.

(Table 1)

2.3 Field experiment

2.3.1 Experimental design

The experimental design was the same for both years: four treatments and four replicates per treatment. The treatments were (1) bare soil (BS) as a control without plant transpiration; (2) cover crops mechanically terminated by crushing in autumn and left as mulch on the soil surface (CC_M) until spring; (3) cover crops mechanically terminated by crushing in autumn and buried by plowing (CC_P) during winter when soil conditions were suitable (to avoid compaction); and (4) cover crops mechanically terminated by crushing in April (CC_L) immediately before sowing the next spring/summer cash crop. The surface area of an elementary plot was 44 and 70 m² in 2017 and 2018, respectively. The preceding cash crop for both years was durum wheat harvested in late June/early July.

Cover crop species were selected for their ability to grow rapidly during the summer and their tolerance to freezing temperatures. They were also selected to favor complementary abiotic resource acquisition, based on previous studies performed under the same climatic conditions (Couëdel et al., 2018b; Tribouillois et al., 2016) and to cover the soil during the entire fallow period due to complementary development. A bispecific mixture was chosen: one crucifer, Ethiopan mustard (*Brassica carinata*), and one legume, crimson clover (*Trifolium incarnatum*). The crucifer grew rapidly after sowing and during autumn. The legume was able to grow during winter under the mustard and could grow more rapidly in early spring, maintaining soil cover and plant transpiration until April.

Seeds were sown respectively at 3 kg.ha^{-1} and 7.5 kg.ha^{-1} of seeds. Shallow tillage was performed in both years before sowing. In both years, 70 mm of irrigation was applied twice after sowing to ensure homogenous emergence and establishment of cover crops to guarantee spatial homogeneity of the soil-crop system. Weeds were controlled on BS using a herbicidal spray in October of both years.

2.3.2 Cover crop biomass and soil water content measurements

Aerial biomass (Mg.ha^{-1}) was sampled from a 0.5 m² area in each replicate plot of the cover crop treatments on each termination date (autumn and spring). Mustard and clover biomass was separated and measured. When present, weed biomass was also measured in the cover crop treatments, but it was always low. Dry matter was weighed after 48 h in an 80°C oven.

SWC (mm) was measured once per month for 8-9 months from cover crop sowing to the following April. The soil profile was sampled from 0-120 cm deep in layers 20 cm thick. Five samples were collected per replicate plot and then pooled by layer for each plot. Measurements in each of the four replicates were taken independently. Soil samples were weighed before and after 48 h in a 105°C oven to measure gravimetric soil moisture (cg water g^{-1} soil).

2.4 Simulation approach

2.4.1 Model overview

We used the soil-crop model STICS (Brisson et al., 2003), which simulates daily crop growth, light, water, C and nitrogen (N) balances based on soil, climate, crop species, and agricultural management. A tipping-bucket approach is used to model the soil, which is divided into five layers with specific characteristics, such as BD, as well as SWC at FC and WP. The water balance was simulated daily by adding soil water supply and subtracting plant transpiration and soil evaporation (Brisson et al., 2009). STICS was evaluated as accurate for a wide range of agro-environmental contexts in France for plant, water, and N outputs for bare soil and many types of cash crops (Brisson et al., 2003; 2009). STICS was also used to simulate cover crops and analyze water, C and N balances and the associated ecosystem services (Tribouillois et al., 2018a). STICS was also successfully evaluated for water drainage (Beaudoin et al., 2008; Constantin et al., 2012).

2.4.2 Model initialization and calibration on-site

2.4.2.1 Soil parameterization and initialization

There was no calibration done on bare soil. Two soils were parameterized separately to simulate each year of the field experiment. For model evaluation, the SWC measured at the beginning of the experiment for each treatment was used, and the soil moisture at FC of each layer was adjusted for each treatment to correspond as closely as possible to field observations. To initialize each soil layer in the model for simulations, the mean SWC and soil mineral N measured in the four treatments at the beginning of the experiment was used for each treatment (Table 1).

(Table 2)

2.4.2.2 Crop calibration

STICS has been calibrated for a wide range of species used as cover crops, such as mustard, rapeseed, radish, ryegrass, oat, pea, vetch, and clover (Constantin et al., 2012; Tribouillois et al., 2018b); however, no parameterization for a mixture of species was available. To simulate the field experiment accurately, we parameterized STICS for the mustard-clover cover crop mixture. The objective was to simulate, as accurately as possible, the main processes governing water balance dynamics, such as cover crop development, biomass growth, changes in soil moisture over time in each soil layer, and total SWC. Starting with parameters already calibrated for rapeseed (the crop most similar to Ethiopian mustard) and crimson clover, we optimized three parameters for cover crop development, N_2 fixation (for clover), and cover crop water requirements to generate the most accurate joint predictions of the dynamics of biomass and SWC in each layer and in total for both experimental years. Mathematical optimization was based on the method developed by Wallach et al. (2011) using the Simplex algorithm, which is available with the STICS model software (Java interface; https://www6.paca.inra.fr/stics_eng).

2.4.3 Water flux simulations of the field experiment

After calibration, model predictions of water drainage, soil evaporation, and plant transpiration were available for each of the four treatments for each year of the field experiment (Table 2); they were used to calculate total water balance and quantify the fluxes. For the 2017 experimental year, simulations began 28 July and ended 28 March. For the 2018 experimental year, simulations began on 1 August and ended on 5 April. Since crimson clover was observed to regrow in both years after being crushed in the CC_M treatment, the model was calibrated to simulate this regrowth as well, using only crimson clover parameters as the crop in a second simulation step.

2.4.4 Simulation of water fluxes over 20 years

To evaluate the impact of cover crops on soil water variables over a long time series, a 20-year simulation was performed using a climate series from 1999-2018, from an INRA weather station installed at the study site. The soil was parameterized and initialized with the field data measured in 2017. Then we run simulations twice, once with dates of technical operations of 2017-crop management for all 20 years and once with dates of the technical operations of 2018-crop management for all 20 years, since each year had different field-operation dates (Table 2). The simulations started on 1 August and finished on 1 April for each year of the 20-year simulation. Predicted SWC and cumulative water drainage on 1 April were also recorded. As in the two-year experiment, potential regrowth of crimson clover after being crushed in the CC_M treatment was simulated.

2.5 Statistical analysis

All statistical analyses were performed using R software (R Core Team, 2018).

2.5.1 STICS evaluation and prediction

2.5.1.1 Model evaluation criteria

Simulations were performed using the model calibrated for the six cover crop treatments (3 treatments × 2 experimental years). Three statistical criteria were used to evaluate the quality of agreement between observed and simulated variables after calibrating STICS for the cover crop mixture – mean deviation (MD), relative root mean square error (rRMSE), model efficiency (EF) – calculated as follows:

$$MD = \frac{1}{n}\sum_{i=1}^{n}(S_i - O_i)$$

$$rRMSE = 100\frac{RMSE}{\bar{O}} \quad \text{with } RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(S_i - O_i)^2}$$

$$EF = \frac{\sum_{i=1}^{n}(O_i - \bar{O})^2 - \sum_{i=1}^{n}(S_i - O_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2}$$

where n is the number of observations; S_i and O_i are the simulated and observed values, respectively, and $\bar{O}$ is the mean value of the observed data.

The three criteria provide a good overview of model performance. MD and rRMSE indicate systematic bias and the dispersal of model simulations compared to observations, respectively. The lower their value, the better is the model prediction. EF, which measures agreement between simulations and observations, varies from 1 (perfect prediction) to $-\infty$. A negative value indicates that the mean of observations is a better predictor than the model.

2.5.1.2 STICS prediction quality

To assess the ability of STICS to simulate biomass, each soil layer's moisture, and total SWC, the relative root mean square error of prediction (rRMSEP) was calculated using cross-validation and a leave-one-out method (Wallach, 2014). The six cover crop treatments were separated into two subsamples: one containing five treatments, to estimate crop parameters, and the other containing the sixth treatment to evaluate the prediction quality of STICS compared to observed data. This procedure was applied six times to assess the prediction quality of STICS for the six treatments by calculating individual RMSEp for each treatment.

$$RMSEp = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(P_i - O_i)^2}$$

$$rRMSEp = 100\frac{RMSEP}{\bar{O}}$$

$$RMSEP = \overline{RMSEp}$$

where P_i are the predicted values.

2.5.2 Field experiment and 20-year simulations

2.5.2.1 Field experiment

Statistical analyses of SWC and soil moisture for each layer in the experiment were performed. Based on the dataset, and after testing the homogeneity of the variables, a non-parametric Kruskall-Wallis test was used to test the impact of the cover crop management practices on the experimental data. A non-parametric Wilcoxon test was used to compare each pair of cover crop treatments. For all analyses, differences among treatments were considered significant at $P < 0.05$.

2.5.2.2 Twenty-year simulations

Statistical analyses of SWC (total and in the 0-10 cm layer) and the difference in drainage predicted in the 20-year simulations were performed. A non-parametric Kruskall-Wallis test was used to test the impact of the cover crop management practices on the simulated data. A non-parametric Wilcoxon test was used to compare each pair of cover crop treatments. For all analyses, differences among treatments were considered significant at $P < 0.05$.

3. Results

3.1 Field experiment

3.1.1 Aerial biomass of cover crop mixtures

On the date of autumn termination for CC_M and CC_P, cover crops reached a mean aerial biomass of 4.2 $Mg.ha^{-1}$ (76% mustard, 24% clover) in 2017 and 3.5 $Mg.ha^{-1}$ (83% mustard, 17% clover) in 2018 (Fig. 2). Afterwards, the clover regrew in CC_M, reaching a biomass of 3.6 and 3.1 $Mg.ha^{-1}$ at the end of the

2017 and 2018 experimental years (early spring), respectively. In contrast, for CC_L at the end of the experimental years, aerial biomass was 7.5 Mg.ha^{-1} (35% mustard, 65% clover) in 2017 and 8.9 Mg.ha^{-1} (88% mustard, 12% clover) in 2018. These results illustrate the temporal complementarity of the two species' growth, which covered the soil throughout the fallow period. Ethiopian mustard develops very quickly in late summer and autumn, while clover growth is particularly important in winter and spring.

(Figure 2)

3.1.2 Soil water measurements during the fallow period

Soil water profiles during the fallow period varied by treatment in both years of the experiment, showing no similar trends or final results (Figs. 3a & b). From July-August to November-December, cover crops had significantly less water under them in the soil profile in 2017 than BS did, but they showed no difference compared to BS in 2018. For both years of the experiment, cover crops and BS showed no difference in SWC during winter. From February to March-April, SWC differed significantly between CC_L or CC_M and BS or CC_P in the layers 20-60 cm deep in 2017 and 2018 (Figs. 3a & b).

(Figure 3a&b)

The change in SWC depended on the yearly rainfall distribution (Fig. 4). In 2017, October and November were dry, each receiving less than 50 mm of rainfall. During these months, measured SWC differed significantly between BS and the cover crop treatments. In December, the difference was ca. 50 mm, due to cover crops having higher actual evapotranspiration (AET) than BS. December and January each received ca. 200 mm of rainfall, which caused soils of all treatments to reach FC. With lower rainfall in March, a significant difference in SWC was observed between BS and CC_P, which had no vegetation, and CC_L and CC_M, which did (Fig. 4a). In 2018, rainfall distribution was more regular than that in 2017. From August-February, 50-100 mm of rain fell each month, which explains the lack of a significant difference among the four treatments during this period. February and March were dry, but resulted in non-significant differences in SWC in the upper layers among the four treatments (Fig. 4b).

(Figure 4a&b)

3.2 STICS calibration and evaluation

3.2.1 Calibration of the cover crop mixture and quality of calibration of STICS for the two years of the experiment

STICS simulated aerial cover crop biomass well: EF was high (0.82) with a non-significant low MD of 0.2 Mg.ha^{-1} of biomass, and rRMSE was only 18.2%. STICS also predicted SWC well, with a high EF (0.87), no significant MD (1 mm of water), and a low rRMSE (4.7%) (Table 3 & Fig. 5) (Supplementary Materials, Figs. S1-S8). STICS predicted water distribution in the soil well, with MD less than 1 cg.g^{-1} and EF always greater than 0.4 for the five soil layers. Dynamics of the upper layers subject to soil evaporation and root uptake of water were simulated accurately, as indicated by an rRMSE of 13.8% and 9.1% for the 0-20 and 20-40 cm layers, respectively. The rRMSE for the three deepest layers was low (< 9%). The dynamics of SWC and the soil water profile were satisfactory (Supplementary Materials, Figs. S1-S8). SWC differed between BS and cover crops somewhat more in the simulations than in the experiment. However, simulation results lay within 1 SD of the observations, indicating that model error was in the same range as the variability in the field measurements.

(Figure 5)

3.2.2 Evaluation of the predictive quality

Using cross-validation to assess the predictive quality of STICS for simulating biomass, soil moisture in each layer, and SWC provided satisfactory results, indicating an acceptable accuracy of the simulations. The rRMSEP of soil moisture were ca. 15% for soil layers 0-40 cm deep and less than 10% for the deeper layers. The rRMSEP of cover crop biomass were less than 10%, and those of SWC were ca. 5% (Table 3).

(Table 3)

3.3 Simulated water fluxes

Like the measurements, predicted SWC was lower for the three cover crop treatments than for BS from late August until the date when FC was reached after winter rainfall (Fig. 6). In 2018, the SWC of cover crops treatments was no more than 15 mm less than that of BS. SWC was 60 mm lower from 50 days after sowing (DAS) to 150 DAS in 2017, while it was 10 mm lower from 20-50 DAS in 2018.

Differences in SWC among the three cover crop treatments depended on the field experiment. No difference in SWC was observed between the three cover crop treatments in 2017, while several differences were measured and simulated in 2018 from 150 DAS. Difference in SWC between CC_M and CC_L first appeared at 150 DAS, resulting in SWC 18 mm higher for CC_M than CC_L in late March. At the same time in March, the SWC for CC_P was the same as that for BS and 70 mm higher than that for CC_M (Table 3). From 170 DAS to the end of the experiment, the difference in simulated SWC increased between BS and CC_P and between CC_L and CC_M, which was similar to the measurements. Simulated SWC decreased more for CC_L and CC_M than for BS and CC_P. The maximum difference in simulated SWC at the end of experiment was 89 mm, which was similar to the difference measured between CC_L and BS (Fig. 6). Simulated cumulative water fluxes for the entire experiment are summarized in Table 4.

For both years of the experiment, higher AET was simulated for all cover crop treatments than for BS, due to an increase in leaf transpiration and a concomitant decrease in soil evaporation due to plant cover. In 2017, the three cover crop treatments had similar simulated evapotranspiration, which was 70 mm higher than BS evaporation. The relative amounts of soil evaporation and plant transpiration differed among the cover crop treatments. CC_P had 77 mm less simulated transpiration than CC_M and 87 mm less than CC_L, which followed the trends for dynamics and amount of aerial biomass. The difference in soil evaporation was inversely proportional to transpiration. In 2018, BS had simulated evapotranspiration 36, 93 and 111 mm lower than those for CC_P, CC_M and CC_L, respectively. The relative amounts of simulated evaporation and transpiration were similar in both years of the experiment for a given treatment (Table 3).

Consequently, cover crops reduced predicted water drainage by the same degree, regardless of their management in a given year. Compared to BS, reductions of ca. 60 and 15 mm were predicted in 2017 and 2018, respectively. Water drained 14 and 10 days later under cover crop treatments than under BS in 2017 and 2018, respectively, indicating a delay in filling in the soil water reserve due to higher AET.

(Figure 6)

3.4 Water balance in the 20-year simulations

For the two 20-year simulations, cover crop biomass simulated for CC_L ranged from 1.9-8.0 ha^{-1} (mean = 5.0 $Mg.ha^{-1}$), indicating that the biomass measured during the experiment corresponded to the largest range of biomass that could be expected at this site. Simulated cover crop biomass for CC_M and CC_P at autumn termination ranged from 2.2-6.6 $Mg.ha^{-1}$ (mean = 4.1 $Mg.ha^{-1}$), indicating that the biomass measured during the experiment lay around the mean biomass that could be expected at this site. The clover regrowth simulated for CC_M ranged from 1.0-3.5 $Mg.ha^{-1}$ (mean = 2.0 $Mg.ha^{-1}$), indicating that its regrowth measured during the experiment corresponded to the largest range of regrowth that could be expected at this site.

Over 20 years, the SWC simulated on 1 April for CC_L and CC_M differed significantly from that for BS (Fig. 7), confirming the potential impact of cover crops on the water supply of the next cash crop in certain years. Simulated mean SWC was 50 mm between CC_L and BS (significantly different) and 60 mm between CC_M and BS, corresponding to the range simulated for the experiment. Simulated mean SWC of CC_P did not differ significantly from that of BS over the 20 years, regardless the management year used (2017 or 2018), and was often near FC. For the 2017 management, mean SWC of CC_L differed significantly from those of CC_P and BS. The impact of CC_M depended greatly on the climate year, with high variability and a mean reduction compared to BS of ca. 60 mm. For the 2018 management, the difference in SWC between BS and CC_M was ca. 20 mm. Differences in simulated SWC were compared for 1 April. BS and CC_P reached FC (or nearly so), with little variability among climate years. Simulated SWC varied greatly for CC_L and CC_M: for 25% of climate years, it was less than 55% of TAWC. Only three of the 20 simulated years showed no difference in SWC between treatments. These years were particularly rainy in winter and spring, which frequently increased SWC to FC. The influence of sowing and termination dates was large, with the difference between SWC for CC_L and CCM_M inverted depending on the year of cover crop management simulated: median SWC for CC_M was ca. 25 mm higher and ca. 15 mm lower than that for CC_L for 2017 and 2018 management, respectively. However, these differences were not statistically significant over the 20 simulated years. Differences in simulated SWC were not due to differences in soil moisture of the 0-20 cm layer, which did not differ significantly on 1 April among the BS, CC_P, CC_M, and CC_L treatments (14.8, 14.8, 15.4, and 15.0 cg.g^{-1}, respectively). SWC simulated over the 20 years differed from that measured in 2017, during which all treatments reached FC, and in 2018, during which cover crops reduced SWC in spring to a degree found at the higher end of the range simulated over the 20 years.

Water drainage for BS ranged from 0-235 mm for the 20 simulated years. Three years had no drainage for both the 2017 and 2018 management years. Mean and median simulated drainage was 67 mm and 48 mm, respectively, which correspond to low drainage at that site. This indicates that the drainage observed during the experiment was among the highest 25% in 20 years, due to the high winter rainfall. The mean difference in drainage of the cover crop treatments compared to BS was 45 mm and 20 mm for the 2017 and 2018 management years, respectively (Fig. 7). These differences represented a reduction in total drainage of ca. 50% and 25% for 2017 and 2018, respectively. For 25% of the 20 years, no drainage was simulated for the three cover crop treatments, unlike under BS, regardless of the management year used. Over 20 years with the 2018 management, CC_M had three years with the same or slightly higher drainage than BS (mean difference = +4 mm). Drainage under cover crops treatments had greater variability than that under BS: in some years, simulated drainage started on the same date under the cover crops and BS, due to a rainy autumn, while in others, drainage started up to 3 months later under cover crops than under BS, especially after a dry autumn. However, the median difference for the beginning of drainage between BS and the cover crop treatments was 14 days, which corresponds roughly to that observed in the experiment.

Like in the experiment, BS had significantly lower simulated AET over the 20 years than the cover crop treatments due to the lack of transpiration. The difference in AET between the three cover crop treatments was small but significant for 2017 management, but not significant for 2018 management. Compared to the other fluxes, AET varied the least over the 20 years.

(Figure 7)

4. Discussion

4.1 Influence of cover crops on soil water content for the next cash crop depends on their termination date

Although the two years of the field experiment had similar cover crop biomass, impact of biomass on the soil water profile differed over time. From sowing to autumn termination in 2017, water depletion was observed along the profile, while in 2018, no difference in the water profile was observed among the treatments. Differences in rainfall dynamics explain why the four treatments showed no differences in the water profile in 2017's spring, while in 2018, there was less water in the soil layers 20-60 cm deep under CC_L and CC_M.

Some studies indicated that cover crops did not influence SWC in spring, as in 2017 in our field experiment (Daigh et al., 2014), while others reported a decrease in SWC due to low rainfall in spring, as in 2018 in our field experiment (Corak et al., 1991; Restovich et al., 2012). Blanco-Canqui et al. (2011) suggested that soil moisture increases from 0-20 cm deep, but we found no difference among the treatments over the experiments or the 20-year simulations. Little rainfall before the last sampling date could have removed differences in soil moisture from 0-20 cm, which could explain why a difference was observed only from 20-60 cm.

The impact of cover crops on the yield of the following cash crop differs in the literature: some studies reported a decrease in yield (Nielsen et al., 2015b), while others reported no negative impacts (Eshel et al., 2015). In some cases, yield can increase after a cover crop, especially when legumes are used (Tonitto et al., 2006). However, these studies did not always identify why yield differed. Yield may decrease due to water stress at the beginning of the cash crop, but it can also be caused by allelopathic effects (Kessavalou and Walters, 1997) or a decrease in soil N content compared to that of bare soil (Tonitto et al., 2006). In both years of the experiment, CC_L and CC_M had lower SWC in soil layers 20-60 cm deep than BS and CC_P at the end of the experiment, which suggests that late termination of a cover crop decreases SWC due to spring transpiration. If spring rainfall is too low to make up for this difference, growth of the next cash crop could decrease. Krueger et al. (2011) highlighted the importance of the termination date on reducing the negative impact of cover crops on yields.

The 20-year simulations showed that cover crops reduced both mean and median SWC simulated on 1 April and that spring rainfall was not sufficient to make up for the cover crops' lower SWC compared to that of BS. Indeed, the effective rainfall: which can indicate refilling of soil water, was positive for only five of the 20 years, and of these five, the soil was refilled up to FC in only two of them. SWC of CC_P did not differ significantly from that of BS, which indicates that sufficient rain fell from termination to early spring to compensate for cover crop transpiration. This indicates that early cover crop termination avoids large differences in SWC in spring between cover crops and bare soil in temperate and Mediterranean climates, as suggested by Alonso-Ayuso et al. (2014). Early termination could be a good way to avoid negative impact, such as pre-emptive competition for water, on the next crop. Termination dates between November and April could be a good compromise to avoid a negative impact on SWC and also could reduce nitrate leaching and soil erosion better and maximize soil C storage. Terminating cover crops before winter could be the best solution in dry regions where water is scarce. Since we tested only two termination dates per year, however, we could not determine an optimal termination date. This should be investigated in the future, such as in a site-specific simulation study.

4.2 Sowing date of cover crops is key to minimizing reduction in drainage

In a recent meta-analysis, Meyer et al. (2019) reported that cover crops reduce water drainage by a mean of 27 mm compared to that under bare soil, but the reduction varies widely among studies. Depending on the year and regardless of the cover crop management, our field experiment indicated that cover crops reduce drainage by 20-60 mm, which lies in the range found in the meta-analysis. Early cover crop termination in autumn or early winter did not influence the reduction greatly, since the same drainage reduction was observed regardless of the termination date or residue management in the two years of the experiment. The 20-year simulations confirmed results of the experiment, showing no difference in drainage reduction among the cover crop treatments for a given sowing date and year. The range of annual reduction in predicted drainage over the 20 years (0-80 mm) was consistent with the variability in results reported in the literature and can explain this variability, since the impact on drainage depends on the interaction between weather conditions and cover crop management. These differences can represent a reduction of nearly 50% in years with high drainage and a complete lack of drainage in drier years. In our experiment, the decrease in drainage due to cover crops was one-third the amount with later sowing (late August) than early sowing (late July). This indicates that sowing date could be a key point to consider when analyzing the impact of cover crops on drainage, as demonstrated by Justes et al. (2017).

4.3 No direct relationship observed between cover crop biomass and impact on water fluxes above a certain level

Compared to bare soil, cover crops increase evapotranspiration by increasing transpiration even though their cover decreases soil evaporation. In the experiment, cover crops increased evapotranspiration by a mean of 30%. This result agrees with the literature (Nielsen et al., 2015a; Qi and Helmers, 2010), in which several studies mention the relationship between biomass and transpiration (Suyker and Verma, 2009; Tolk and Howell, 2009). However, no significant relationship was observed between cover crop biomass and evapotranspiration or drainage in either year of the experiment. Tribouillois et al. (2018) reported a correlation between cover crop biomass and an evapotranspiration. They assessed cover crops with lower biomass (0.5-2.5 Mg.ha^{-1} yr^{-1}) than we did

(> 8 Mg.ha^{-1}). Crops transpiration is linked with the biomass through the leaf area index (LAI) and it is assumed that above a certain level of LAI, transpiration does not increase in proportion, and remains constant from a certain level (Kang et al., 2003; Kristensen, 1974). This could explain why we did observed no correlation between cover crop biomass and evapotranspiration or drainage. Tribouillois et al. (2018b) also reported a strong negative correlation between the mean decrease in annual drainage and the mean increase in annual evapotranspiration due to cover crops. This latter result was found in the 2017 experimental year. However, in 2018, no significant correlation was observed between the difference in drainage and evapotranspiration. The increase in evapotranspiration influenced not only drainage, which decreased only slightly, but also the soil water content in spring, which was much lower for CC_L and CC_M than for BS. This could have been due to differences in rainfall distribution during the fallow period.

4.4 Study boundaries

4.4.1 Field experiment and simulations

Irrigation was applied after sowing the cover crop to ensure homogenous emergence and establishment. Irrigation in summer, which is a dry period in southwestern France, could explain the large amount of biomass observed, since strong growth of juvenile stages favored crop establishment. Since we included irrigation in the 20-year simulations, STICS also predicted large amounts of biomass. However, farmers in the region currently do not irrigate cover crops. Consequently, water stress could occur with an early sowing date, such as July or early August in our conditions, which could result in lower biomass. The impact of cover crops on the water balance could change, since the climate in southwestern France is dry in summer, and August rain is not always sufficient to ensure adequate emergence and development of cover crops to produce a sufficient amount of biomass. To evaluate the impact of irrigation, we also performed the 20-year simulations without irrigation. The results (not shown) indicated that drainage was slightly lower, but not significantly so. Predictions for the impact on SWC and the difference in drainage compared to BS were similar with or without irrigation. Without irrigation, the cover crop did not develop in some dry summers, or developed later. In such cases, cover crops would not influence water fluxes.

The field experiment was performed on two similar soils at the same INRA experimental station. The soils had high SWC due to their great depth. More investigation is required to determine the importance of cover crops on shallow soils. On shallow soils, cover crops could have less impact on drainage due to less water lost via transpiration because their roots would not extend as deep.

In 2018, soil texture in the deeper layers of the field plot varied greatly, even over short distances, which could have masked significant differences in SWC due to cover crop treatments, as predicted in the 20-year simulation. This highlights the ability of the strong complementarity between field experiments and modeling to help understand and quantify dynamic interactions between treatments and weather conditions.

4.4.2 STICS parameterization and initialization

An initial step in our study was to evaluate the ability of STICS to predict aerial biomass of cover crops and SWC over time for the entire fallow period to obtain satisfactory water flux simulations. Biomass and SWC were simulated sufficiently well for both years and were similar to or even an improvement on results of previous studies (Brisson et al. 2002; Coucheney et al. 2015). STICS, already used successfully to simulate drainage under cover crops (Constantin et al., 2012; Tribouillois et al., 2016), remained accurate in our study. We can therefore assume that STICS simulated the fluxes under different management practices sufficiently well. Nonetheless, we could have improved calibration of the cover crop mixture had we measured dynamics of the leaf area index, since leaf area governs transpiration.

SWC predictions would have been more accurate if soil water content had been initialized for each treatment based on measurements. However, we initialized the soil with the mean SWC measured in the four treatments to ensure that differences in simulated water fluxes would be due only to the management practices, not to different initial states caused by natural field variability. Consequently, STICS slightly overestimated the difference in SWC between CC_L and BS in 2018 and thus could have slightly overestimated the difference in drainage and evapotranspiration between cover crops and BS. Nevertheless, the simulated SWC always lay within 1 SD of observed values, which indicates that overestimates were consistent with experimental results and that predicted differences in water balance among treatments were acceptable.

4.5 Cover crop residues left as mulch can reduce soil evaporation and thus actual evapotranspiration

One objective of our study was to analyze the impact of cover crop residues left as mulch via mechanical crushing after the first autumn termination (CC_M) on the water balance, since no reference was available in the literature, despite this practice's great benefit for farmers. Although not planned, the crimson clover regrew after crushing and produced a large amount of biomass. Consequently, CC_M caused changes in the water balance similar to those of CC_L. Cover crop mulch can increase SWC in the surface layer by reducing evaporation (Alliaume et al., 2014; Moschler et al., 1967; Stipešević and Kladivko, 2005), but we did not observe this effect for clover regrowth in the field experiment. It is well known that residue mulch decreases evaporation. Evapotranspiration under a cover crop terminated early and left as mulch could result in the same cumulative AET as that under bare soil, since compared a bare soil, AET would be higher during cover crop growth, and soil evaporation would be lower after cover crop termination. Thus, a cover crop terminated early and left as mulch could reduce drainage less than a cover crop terminated late. It could also increase soil moisture on the surface (i.e. 0-10 cm) and avoid an overly dry seedbed when the next cash crop is sown. However, it could also make the soil too wet for sowing and cause bearing-capacity problems. This demonstrates that cover crop management, especially the termination date, is important for cover crops to provide a sufficient level of services, such as capturing nitrate or improving soil physical properties (Alonso-Ayuso et al., 2018). In dry areas where water is scarce, cover crops can reduce drainage and shallow groundwater recharge, and we hypothesis that mulching could be a good practice to maintain the services expected from cover crops, resulting in a good comprise between services and disservices. Thus, this practice could encourage green manure or catch crop services and avoid disservices by minimizing negative impacts on water-balance fluxes due to pre-emptive competition for water, which reduces drainage and water availability for the next cash crop.

Conclusion

The choice of cover crop termination date and management of cover crop residues could be a way to benefit from all the services they provide, such as the green manure effect or increasing soil physical properties in agroecological systems, while reducing their potential negative effects on the water balance. Our study highlighted the impact of different cover crop management practices and the variability of their water balance compared to that of bare soil. Cover crops clearly increase AET and reduce drainage, but do not always reduce SWC at sowing of the next cash crop, which depends greatly on the rainfall after cover crop termination. A decrease in groundwater recharge must be considered when generalizing cover crops at the regional scale, especially that of shallow groundwater, which is determined by drainage from agricultural soils. We demonstrated that later termination of cover crops could have a negative impact on the next cash crop, even when depending on spring rainfall. However, an optimal solution for cover crop management could include mechanically crushing the cover crop in autumn and leaving the residues as mulch but new experiments must be carried out to verify this hypothesis. Studies that combine field experiments and simulation modeling are required to assess this management practice for other soil and climate conditions, since the issue is also site-specific due to interactions between soil type and depth, and the amount and distribution of rainfall. The potential of cover crop mulch to reduce soil evaporation before sowing the next cash crop could be a good compromise between improving cover crop services and decreasing negative impact on the water balance and its resulting consequences.

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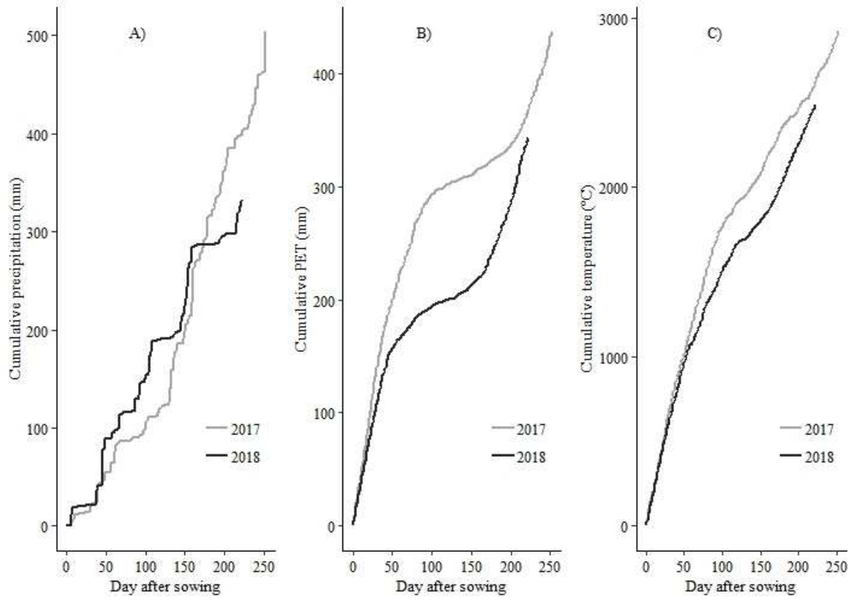

Figure 1. Cumulative (A) rainfall, (B) potential evapotranspiration (PET), and (C) temperature of the study site after sowing cover crops during the 2017 and 2018 experimental years.

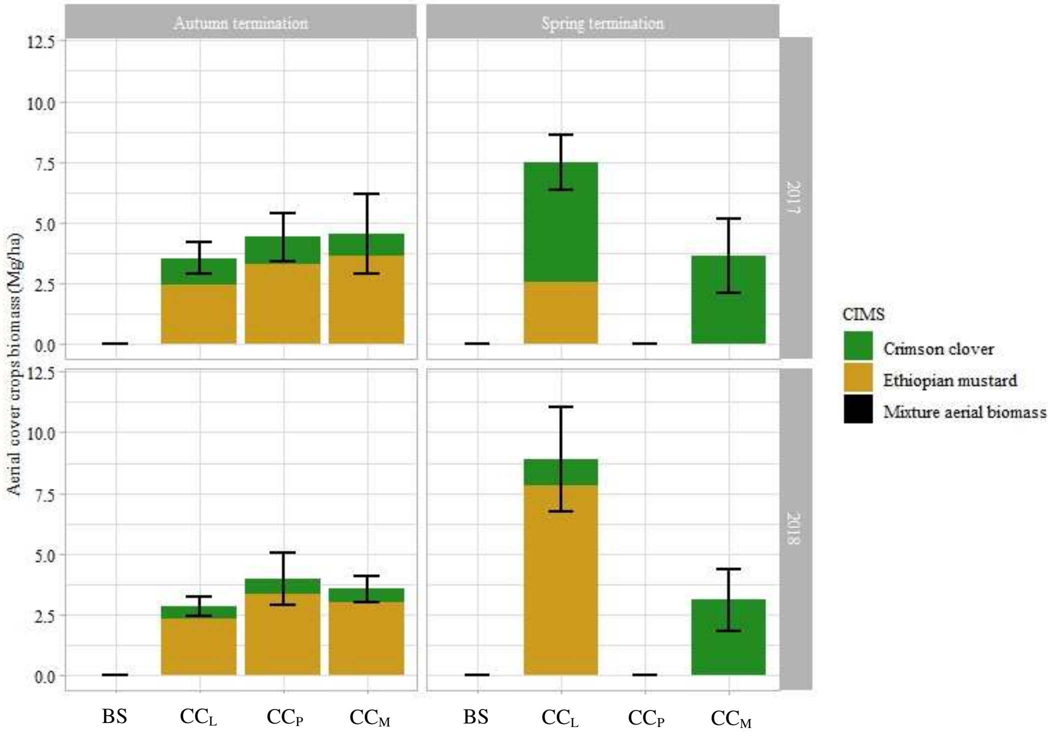

Figure 2. Cover crop biomass at (left) autumn or (right) spring destruction in the (top) 2017 and (bottom) 2018 experimental years for the four treatments: bare soil (BS), cover crop crushed in autumn and left as mulch on the soil surface (CC$_M$), cover crop crushed in autumn and buried by plowing (CC$_P$), and cover crop destroyed in April (CC$_L$). Error bars represent ±1standard deviation.

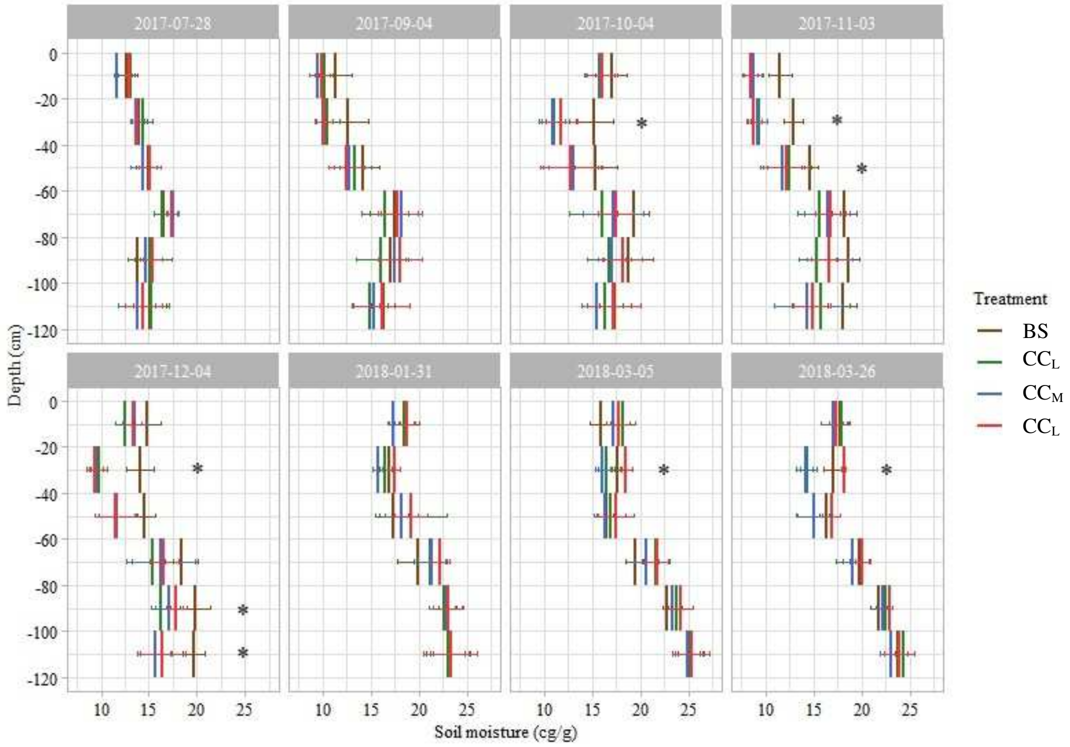

Figure 3a. Mean soil moisture (cg g^{-1} soil) in each 20 cm layer in the 2017 experiment for the four treatments: bare soil (BS), cover crop crushed in autumn and left as mulch on the soil surface (CC$_M$), cover crop crushed in autumn and buried by plowing (CC$_P$), and cover crop destroyed in April (CC$_L$). Horizontal error bars represent ±1 standard deviation. Asterisks indicate a significant ($P < 0.05$) difference according to the Kruskal-Wallis test.

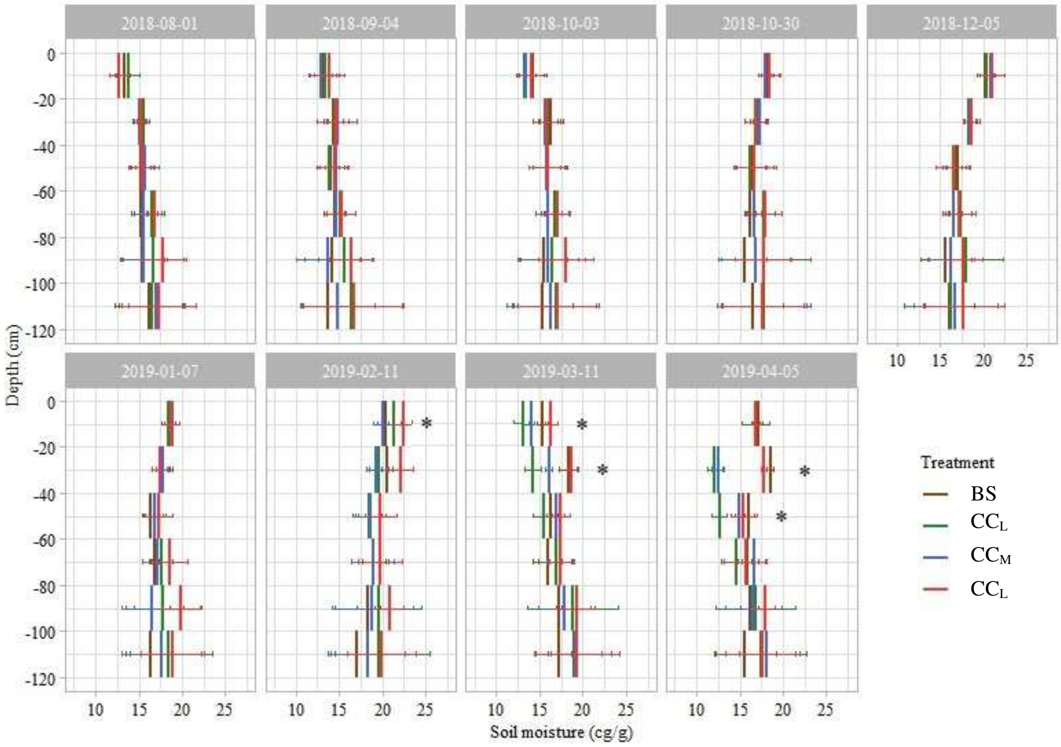

Figure 3b. Mean soil moisture (cg g^{-1} soil) in each 20 cm layer in the 2018 experiment for the four treatments: bare soil (BS), cover crop crushed in autumn and left as mulch on the soil surface (CC_M), cover crop crushed in autumn and buried by plowing (CC_P), and cover crop destroyed in April (CC_L). Horizontal segments represent ±1 standard deviation. Asterisks indicate a significant ($P < 0.05$) difference according to the Kruskal-Wallis test.

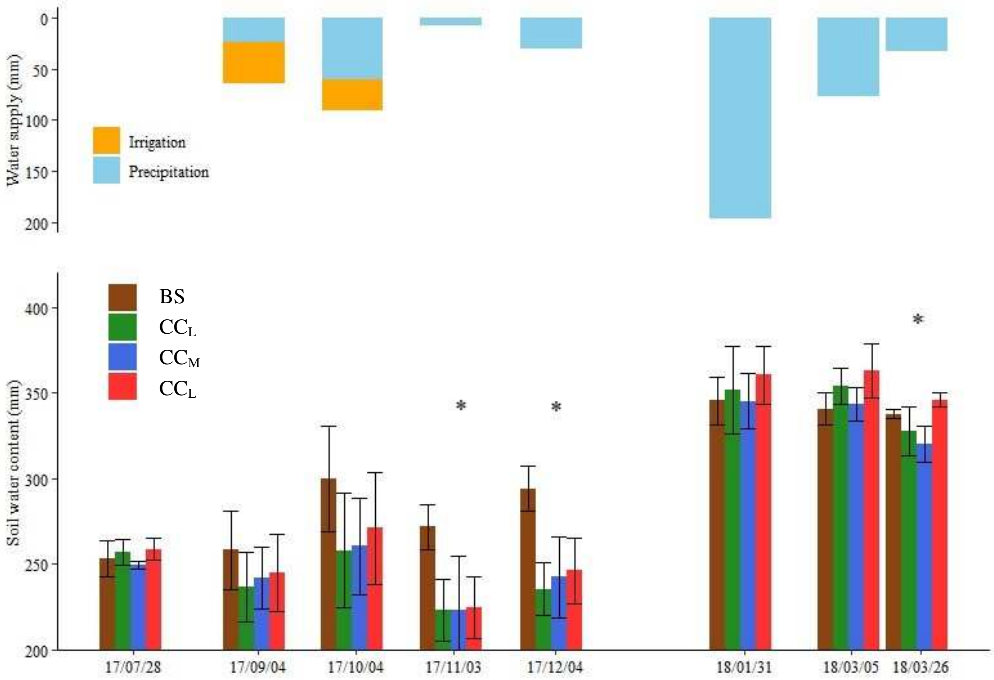

Figure 4a. (top) Water supply (irrigation + rainfall) and (bottom) soil water content (0-120 cm deep) between each gravimetric measurement in the 2017 experiment for the four treatments: bare soil (BS), cover crop crushed in autumn and left as mulch on the soil surface (CC_M), cover crop crushed in autumn and buried by plowing (CC_P), and cover crop destroyed in April (CC_L). Error bars represent ±1standard deviation. Asterisks indicate a significant ($P < 0.05$) difference according to the Kruskal-Wallis test.

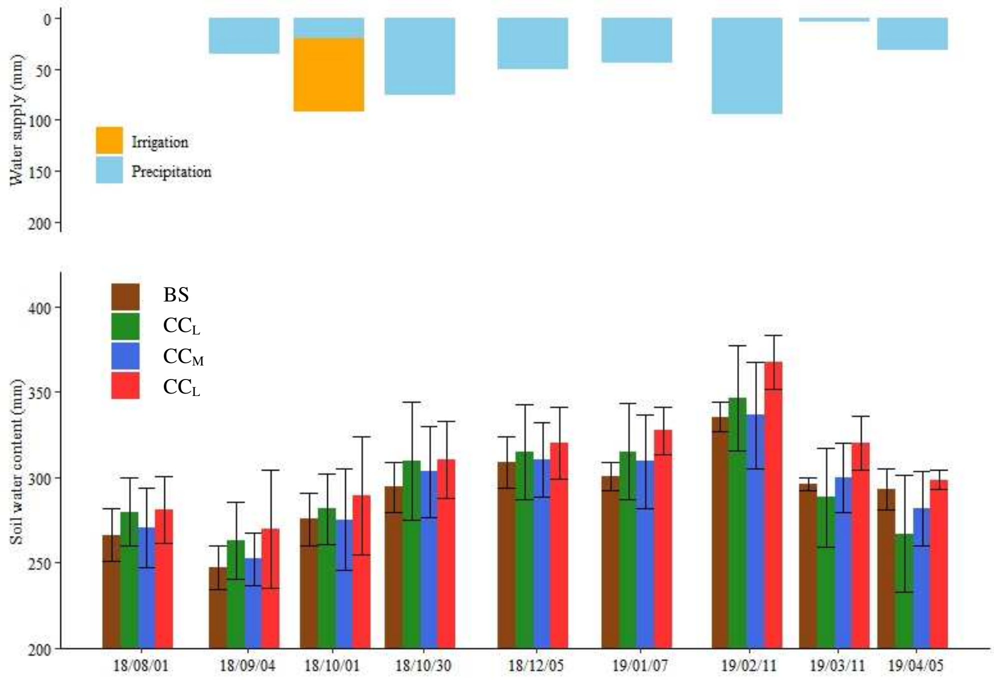

Figure 4b. (top) Water supply (irrigation + rainfall) and (bottom) soil water content (0-120 cm deep) between each gravimetric measurement in the 2018 experiment for the four treatments: bare soil (BS), cover crop crushed in autumn and left as mulch on the soil surface (CC_M), cover crop crushed in autumn and buried by plowing (CC_P), and cover crop destroyed in April (CC_L). Error bars represent ±1standard deviation.

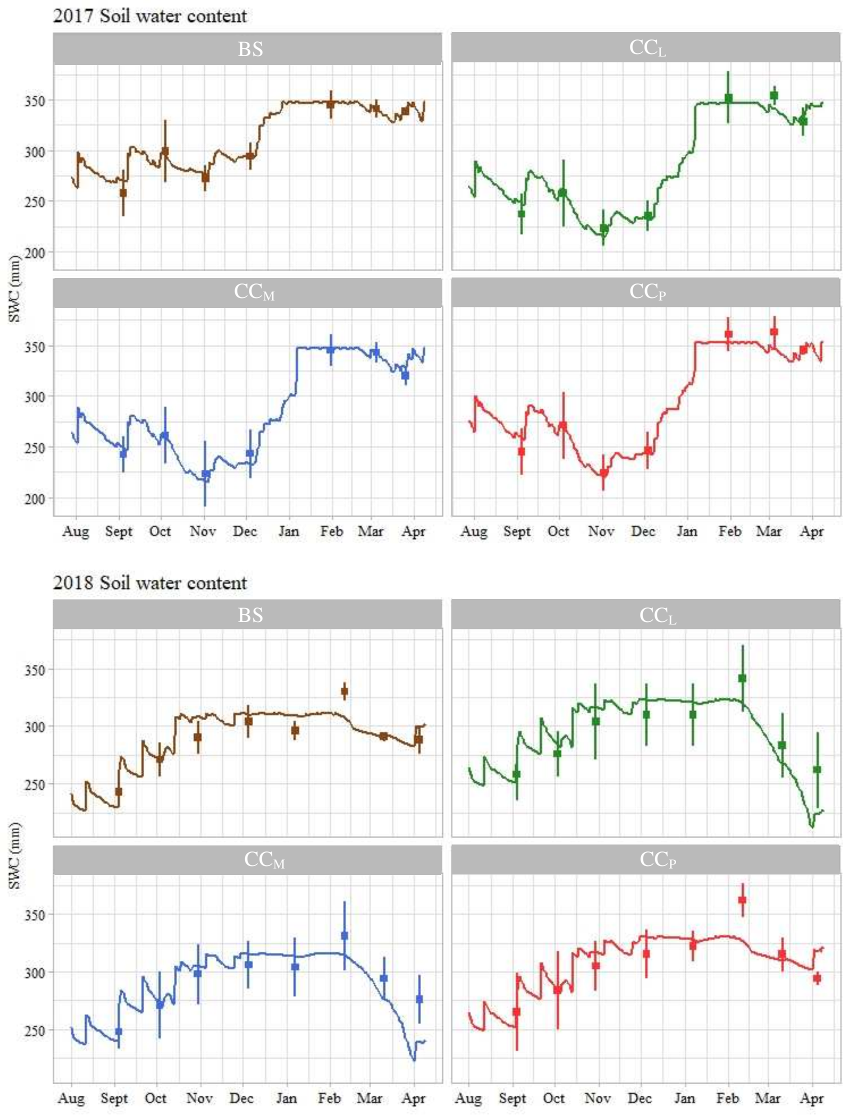

Figure 5. Predicted dynamics of soil water content (0-120 cm deep) during the (top) 2017 and (bottom) 2018 experimental years for the four treatments: bare soil (BS), cover crop crushed in autumn and left as mulch on the soil surface (CC$_M$), cover crop crushed in autumn and buried by plowing (CC$_P$), and cover crop destroyed in April (CC$_L$). Squares represent observed mean soil water contents, and error bars represent ±1 SD.

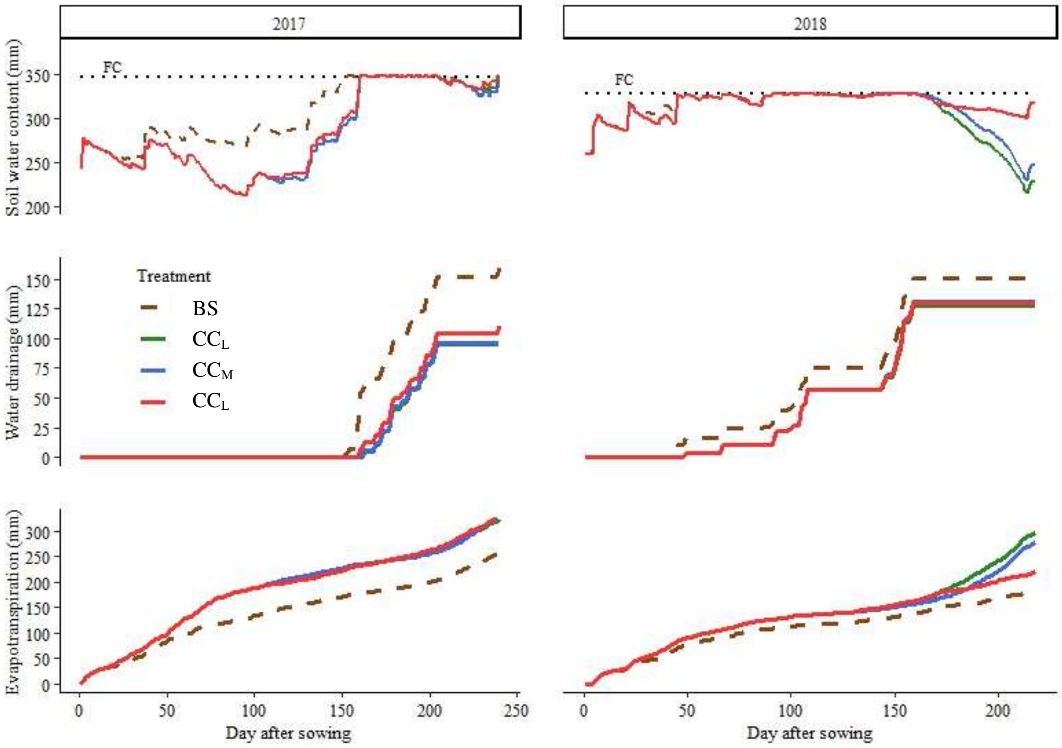

Figure 6. (top) Soil water content (0-120 cm deep), (middle) water drainage, and (bottom) evapotranspiration after sowing cover crops during the (left) 2017 and (right) 2018 experimental years for (dashed lines) bare soil (BS) and (solid lines) the three cover crop treatments: cover crop crushed in autumn and left as mulch on the soil surface (CC$_M$), cover crop crushed in autumn and buried by plowing (CC$_P$), and cover crop destroyed in April (CC$_L$). Dotted lines represent field capacity (FC).

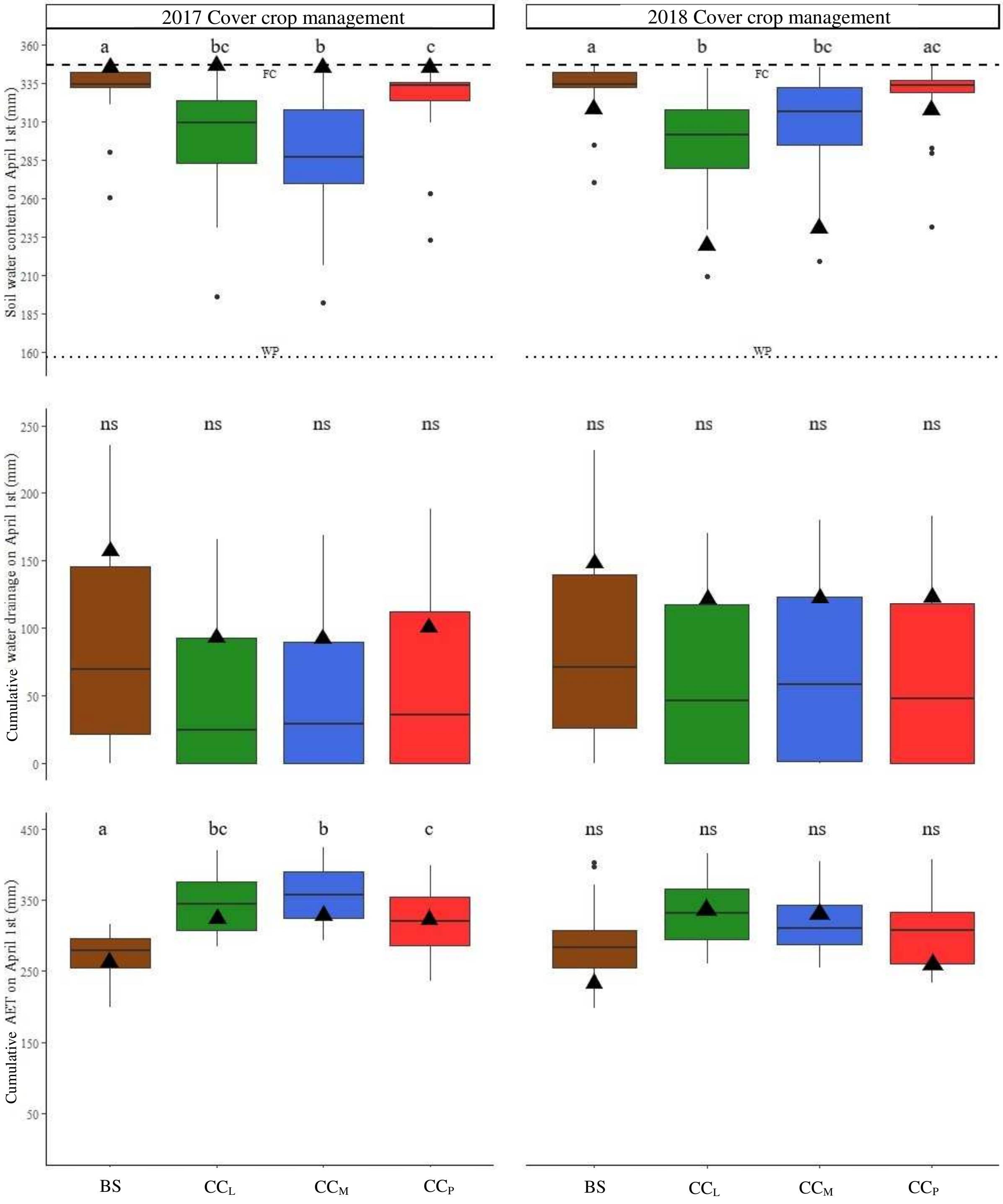

Figure 7. Boxplots of (top) soil water content (0-120 cm deep), (middle) cumulative drainage, and (bottom) cumulative AET on 1 April in the (left) 2017 and (right) 2018 experimental years according to the four treatments: bare soil (BS), cover crop crushed in autumn and left as mulch on the soil surface (CC_M), cover crop crushed in autumn and buried by plowing (CC_P), and cover crop destroyed in April (CC_L). Dashed lines represent field capacity, while dotted lines represent wilting point. triangles represent the fluxes simulated for the 2017 and 2018 experimental years. Different letters indicate a significant difference ($P < 0.05$) between treatments. ns: no significant difference. Each experimental year was analyzed separately.

Table 1. Mean soil texture and physical properties by soil layer at the study site in 2017 and 2018

Experiment	**Depth (cm)**	**Clay (%)**	**Loam (%)**	**Sand (%)**	**Bulk density ($g\ cm^{-3}$)**	**Field capacity ($cg\ g^{-1}$)**	**Wilting point ($cg\ g^{-1}$)**
2017	0 – 20	25.8	30.7	43.5	1.50	17.8	8.9
	20 – 40	24.8	30.0	45.2	1.50	17.5	8.8
	40 – 60	28.2	30.1	41.7	1.50	17.1	8.5
	60 – 80	38.9	33.5	27.6	1.45	20.0	13.5
	80 – 100	38.6	40.0	21.4	1.40	23.6	13.9
	100 – 120	31.3	47.4	21.3	1.40	23.6	11.8
2018	0 – 20	24.7	31.4	43.8	1.45	20.0	10.0
	20 – 40	23.3	31.0	45.7	1.45	20.0	10.0
	40 – 60	22.1	32.0	45.9	1.45	17.5	8.7
	60 – 80	21.2	29.7	49.1	1.50	18.0	9.0
	80 – 100	20.3	26.6	53.1	1.50	17.8	8.9
	100 –120	20.8	28.5	50.7	1.5	17.8	8.9

Table 2. Cover crop management at the study site in 2017 and 2018 for the four treatments: bare soil (BS), cover crop crushed in autumn and left as mulch on the soil surface (CC_M), cover crop crushed in autumn and buried by plowing (CC_P), and cover crop destroyed in April (CC_L).

Characteristic	**2017**				**2018**			
Previous crop	Durum wheat				Durum wheat			
Treatment*	BS	CC_M	CC_P	CC_L	BS	CC_M	CC_P	CC_L
Sowing date	-	31 July			-	28 Aug		
Destruction date	-	15 Nov	15 Nov	11 Apr	-	07 Jan	07 Jan	09 Apr
Plowing date	13 Dec	-	13 Dec	-	08 Jan	-	08 Jan	-

Table 3. Relative root mean square error of predictions (rRMSEP) of interest of the STICS model

	Soil moisture ($cg\ g^{-1}$)						Cover crop biomass ($Mg.ha^{-1}$)
	0-20 cm	20-40 cm	40-60 cm	60-80 cm	80-120 cm	0-120 cm	
rRMSEP (%)	15.2	13.0	8.1	5.9	8.5	5.6	9.2

Table 4. Simulated soil water cycle variables for 2017 and 2018 (all in mm) in the four treatments: bare soil (BS), cover crop crushed in autumn and left as mulch on the soil surface (CC_M), cover crop crushed in autumn and buried by plowing (CC_P), and cover crop destroyed in April (CC_L). SWC = soil water content.

Experiment	**Treatment**	**Initial SWC**	**Evaporation**	**Transpiration**	**AET**	**Drainage**	**Final SWC**
2017	BS	254	269	0	269	158	347
	CC_P	254	229	111	341	110	347
	CC_M	254	151	188	340	97	343
	CC_L	254	136	198	335	95	347
2018	BS	275	236	0	236	150	317
	CC_P	275	201	71	272	130	316
	CC_M	275	149	180	329	131	246
	CC_L	275	134	213	347	127	228