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To cite this version:

Nicolas Meyer, Jacques-Eric Bergez, Eric Justes, Julie Constantin. Influence of cover crop on water and nitrogen balances and cash crop yield in a temperate climate: A modelling approach using the STICS soil-crop model. European Journal of Agronomy, 2022, 132, pp.126416. 10.1016/j.eja.2021.126416 . hal-03538874

HAL Id: hal-03538874
https://hal.inrae.fr/hal-03538874v1

Influence of cover crop on water and nitrogen balances and cash crop yield in a temperate climate: a modelling approach using the STICS soil-crop model

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Key words

drainage; evapotranspiration; catch crops; sowing date; termination date; residue management

Highlights

- Cover crops (CC) decreased nitrate leaching and drainage according to sowing date
- CC decreased total soil water content at cash crop sowing but not that of seedbeds
- Cash crop yield decreased mainly due to N stress, especially with late CC termination
- CC, even terminated late, did not cause water stress that decrease cash crop yield

Abstract

Cover crops are crucial to diversify cropping systems into more agroecological systems by providing ecosystem services, such as reduction of nitrate leaching, provision of a green manure effect, and soil carbon storage. However, they can influence water drainage and nitrogen (N) or water availability for the succeeding crop, depending on their management and the climate. In this simulation study, we used the STICS model to predict the influence of cover crop species, date of sowing and termination, and cover crop residue management on N and water balances, and the yield and stress of the succeeding cash crop. We performed 25-year simulations for five contrasting sites in south-western France, which is a temperate region of Europe with dry summers. As expected, cover crops decreased nitrate leaching effectively but also decreased drainage by a mean of 5-40 mm. This decrease depended mainly on the sowing and termination dates, while the decrease in nitrate leaching varied greatly among sites and depended most on sowing date, followed by cover crop species and then termination date. Cover crops had little influence on soil water content in the upper 0.1 m of soil at sowing of the succeeding cash crop, but decreased soil water content of the total soil profile by 0-30 mm. Soil water content depended most on termination date, followed by species and then site. Total soil mineral N content (SNC) also decreased, by 5-40 kg N.ha^{-1}, at the three driest sites and up to 10 kg N.ha^{-1} at the rainiest site. Termination date, the second-most influential factor on SNC, indicated that later termination resulted in lower SNC than that after bare soil. N uptake by the succeeding cash crop depended on species and termination date, and a legume cover crop and earlier termination date resulted in higher N uptake. The decrease in maize and sunflower yield was due mainly to changes in the N stress index during the vegetative phase for maize, and both vegetative and reproductive phases for sunflower. No water stress or increase in irrigation volumes was predicted or was correlated with yield changes, except at dry sites for the few years that experienced a severe drought in spring. While cover crops decreased nitrate leaching effectively, they decreased drainage and could induce N stress for the succeeding crop, particularly in dry regions. Including legumes in mixtures and adapting the termination date to local climate conditions could decrease or avoid these negative effects.

1. Introduction

Cover crops, also called catch crops or green manure, are one of the pillars of agroecological practices and are essential for diversifying cropping systems (Duru et al., 2015). Sown during the fallow period between two annual cash crops and usually terminated long or immediately before sowing the succeeding cash crop, they are returned to the soil. Cover crops can provide a wide range of ecosystem services, such as provision of a green manure effect; storage of carbon in the soil; reduction of nitrate leaching and erosion, a better greenhouse gas balance and weed control (Constantin et al., 2010; Ryder and Fares, 2008; Schipanski et al., 2014; Tonitto et al., 2006; Tosti et al., 2014; Tribouillois et al., 2018).

As cover crops increase evapotranspiration during the fallow period compared to bare soil (Unger and Vigil, 1998) and take up mineral nitrogen (N) from the soil, they change water and N balances during and following this period. Cover crops generally decrease drainage (Meyer et al., 2019) and can decrease soil water content (SWC) before sowing of the succeeding crop, particularly when they are terminated immediately before sowing (i.e. "late termination") (Meyer et al., 2020). The increase in water and mineral N uptake can decrease water and N availability for the succeeding crop, and this pre-emptive competition occurs particularly in dry regions (Thorup-Kristensen et al., 2003). In the context of climate change, with temperatures and lower rainfall in arid and temperate regions (IPCC, 2013), sowing cover crops during the fallow period could increase issues for groundwater recharge and decrease yield of the succeeding cash crop, by reducing drainage (Tribouillois et al., 2018) and soil water and N availability for the following crop (Alonso-Ayuso et al., 2018; Meyer et al., 2020).

The magnitude of these processes depends on the soil, climate and cover crop management, such as choice of species, dates of sowing and termination, and residue management (Constantin et al., 2015b; Meyer et al., 2019; Tribouillois et al., 2015a). Some field-experiment studies highlighted the importance of the termination date to avoid hindering the succeeding cash crop (Alonso-Ayuso et al., 2014; Clark et al., 1997). Some showed that cover crops without late termination could decrease nitrate leaching effectively, as well as the risk of decreasing drainage and yield for the succeeding crop (Constantin et al., 2015b). A meta-analysis by Tonitto et al. (2006) highlighted that, under certain conditions, the green manure effect of a legume cover crop can replace mineral N fertilisation for maize (*Zea mays* L).

Understanding these interactions and their potential positive or negative influence on the succeeding cash crop is crucial for farmers and agricultural advisers to manage cover crops better. This can provide the best compromise for supplying ecosystem services without producing dis-services for the succeeding cash crop.

Thus, cover crop management is crucial to avoid or limit the cover crop's potential negative influence on the succeeding crop. Management practices should be adapted locally to a site, its soil and climate characteristics, and the succession of cash crops, which determine the degree of potential pre-emptive competition. Crop models can be a valuable tool to assess the influence of cover crops on water and N balances under multiple cropping system management practices, particularly over large areas (Bergez et al., 2010). The objective of the present study was to quantify the influence of cover crop management scenarios on water and N balances and on the succeeding cash crop in multiple soils and climates at the regional scale. The study was conducted for the Adour-Garonne catchment (120 000 km²), a large catchment in south-western France which has frequent water deficit in aquifers during summer and irrigation restriction (Mazzega et al., 2014), using the STICS soil-crop model (Brisson et al., 2009, 2003).

2. Materials and methods

2.1. Study area

The study area was located in the Adour-Garonne catchment, in south-western France (Figure 1). This area of France has a temperate climate, with several climate types according to the definitions of Joly et al. (2010): mainly oceanic, altered oceanic, semi-continental and south inland oceanic from west to east. Conditions during the summer, when cover crops are sown, vary, with wet and warm conditions in the west with an oceanic influence, and dry and hot conditions in the east. Soils in this catchment range from sandy soils in the west to more clayey soils in the east. The catchment aquifers are also influenced by nitrate pollution in winter and a water deficit in summer. To represent the range of soils and climates in the catchment, we chose five agricultural fields, from west to east: RDL, LAL, LEC, AUZ and PEY.

2.2. Virtual experimental design

The simulation approach consisted of using the STICS soil-crop model (Brisson et al., 1998; 2002; 2003; 2009) to simulate the fallow period and the succeeding crop for five soil-climate combinations over 18 years. We tested several fallow-period management practices, including bare soil or cover crops of multiple species, sowing and termination dates and cover crop residue management practices, which were followed by maize or sunflower (*Helianthus annuus*) in a continuous simulation to take into account the effect of cover crop residues on the cash crop. The simulation were re-initialized at each beginning of the fallow period to avoid the cumulative effect of cover crops (Constantin et al., 2011). For all five sites, we simulated bare soil as a control and four types of cover crops commonly sown during the fallow period between a winter and spring crop: white mustard (*Sinapis alba*), common vetch (*Vicia sativa*), Italian ryegrass (*Lolium multiflorum*) and a bispecific mixture of red clover (*Trifolium incarnatum)* and Ethiopian mustard (*Brassica carinata*). These four types were selected for their contrasting growth, production and potential biomass C:N ratio; variable sensitivity to water stress, high temperatures and frost; and contrasting sensitivity to soil mineral N availability (i.e. legume vs. non-legume).

We tested four cover crop sowing dates (August 5, August 20, September 5 and September 20), combined with four cover crop termination dates from late autumn to early spring (November 15, December 15, March 15 and April 15) (Table 1). At termination, we simulated two cover crop residue-management practices: ploughed or left as mulch on the soil surface. Finally, we simulated two cash crops sown on April 16: irrigated maize, with automatic irrigation triggered by the STICS model if a water satisfaction index fell below 85%, and sunflower grown under rainfed conditions (without irrigation). Mineral N inputs for the cash crops were determined from surveys of cropping practices in the Adour-Garonne catchment. N fertilisation was 185 kg N ha^{-1} divided into two applications for maize and 50 kg N ha^{-1} two weeks after sowing for sunflower. The simulations were conducted over 1990-2017 to represent the actual climate variability of each site. For each cash crop, year and site, we ran 129 “species × sowing date × termination date × residue management” scenarios.

(Insert Table 1 around here)

2.2.1. Climate and soil data

The five sites covered a wide range of climate variability in the Adour-Garonne catchment for arable farming areas outside of mountain areas. We used the climate in the SAFRAN climate grid cell (Durant et al., 1993) which corresponded to each location from 1990-2017. Over the 18 years, mean annual rainfall (R) per site ranged from 650-1200 mm yr^{-1}, mean potential evapotranspiration (PET) ranged from 790-950 mm yr^{-1}, and mean annual temperature ranged from 13.2-13.8°C yr^{-1}. The monthly mean of the difference between rainfall and PET, an indicator of water deficit, indicated substantial climate differences among the sites. Two wet sites (LAL and RDL) had no water deficit (R-PET > 0) for 7-8 months, with the deficit only in summer. The other three sites had a water deficit for a mean of nearly 8 months per year over the 18 years (Figure 1).

(Insert Figure 1 around here)

Soil texture differed among the five sites, ranging from sandy to silty clay according to the texture triangle (Jamagne et al., 1977). To match the West to East gradient with sandy to clay soils in the catchment, we selected a sandy soil for RDL, silt loam for LAL, silty clay soil for LEC and clay loam soils for AUZ and PEY. SWC at field capacity and permanent wilting point were estimated from texture using pedotransfer functions (Table 2). For the five sites, we set soil organic N content in the upper 0.25 m of soil at 9 g N kg^{-1} and asset soil depth to 0.9 m to compare sites more easily, especially their water drainage.

(Insert Table 2 around here)

2.3. Simulation methods

2.3.1. STICS model overview

The STICS soil-crop model is a dynamic process-based model that runs on a daily time step. It simulates crop growth and water, carbon and N balances under the influence of weather, soil and crop management practices. STICS simulates cropping systems over time, from a crop cycle to a long-term succession, including the management of fallow periods between cash crops. Soil water is modelled using a "tipping-bucket" approach. Water demand uses a crop-coefficient approach, while N demand is based on the N dilution curve, which is generic and robust (Gastal and Lemaire, 2002). Depending on the SWC and soil mineral N content (SNC) in the rooting zone, water and N stresses decrease crop growth when demands are not met by soil availability. When residues are left on the soil surface, the mulch decreases soil evaporation as a function of the amount of biomass in the mulch. Mulch can also intercept some rainfall and irrigation, and this water, retained in the mulch, evaporates according to the evaporative demand (Brisson et al., 2009). STICS has been evaluated for French soil and climate contexts and for several crops, including cash and cover crops (Coucheney et al., 2015). These authors classified STICS' predictions as "satisfactory" to "very good" for most of the variables analysed, especially the SWC and crop biomass under differing levels of N and water availability. STICS has been used to simulate cover crops, in particular to predict their influence in the short to long terms on the SWC, SNC and the green manure effect (Constantin et al., 2012; Tribouillois et al., 2018). Cover crop species simulated in the present study were previously calibrated and validated for STICS based on several field experiments (Constantin et al., 2015b; Meyer et al., 2020). The version 10 of STICS was used in this study as in Meyer et al. (2020). Even if the version is different from the one used in the main paper on STICS evaluation by Coucheney et al. (2015), the evolution of STICS is conducted by the STICS team with automatic evaluation of the model accuracy on the same database as used in this paper. The fitting obtained by the following versions of the model are checked to give similar results. The level of accuracy for the different variables analysed in this paper are then still very close.

2.3.2 STICS model initialisation

Soil water and mineral N were initialised in STICS in the same way for all five sites. To initialise the SWC of each soil layer, we simulated a wheat crop preceding the sowing of the cover crop. Thus, water initialisation differed for each climate year, which depended on the weather of the previous year. We initialised the SNC of the soil profile with a low SNC of 18 kg ha^{-1}, homogeneously distributed over the soil profile. This value corresponds to that after a well-managed wheat crop, for which the uptake of N by a cover crop is more likely to influence the succeeding crop.

2.4. Data analysis and statistics

Soil-crop models produce many output variables. The selected STICS outputs we focused on were : (1) cover crop biomass at termination; (2) cumulative water drainage, evapotranspiration and nitrate leaching during the fallow period and the crop succession; (3) SWC and SNC at cash crop sowing and (4) irrigation volume simulated by the STICS model according to the maize water requirement, water (WSI) and N (NSI) stress, and yields of the succeeding cash crop. For SWC, we analysed it over the whole profile and in the seedbed (upper 0.1 m of soil). We calculated differences and ratios of the outputs of interest between the cover crop management (i.e. each species, sowing and termination dates, and residue management) and bare soil per site and year.

We analysed the influence of the factors site, cover crop species, sowing date, termination date, and residue management on the outputs of interest using analysis of variance (ANOVA) within the R software (https://cran.r-project.org/), considering climate years as replicates. After testing the normality and homogeneity of the variances in the simulated outputs, we used the ANOVA to determine the percentage of variance explained by each factor and their interactions, as all factors were significant due to the large number of simulations. We ranked the factors in descending order of explanation of variance for each output of interest. We also calculated correlations between changes in water and N stress due to differences in cover crops and yields for maize and sunflower compared to bare soil.

3. Results

3.1. Bare soil

As expected, predicted drainage varied greatly among sites and was related to contrasting levels of rainfall and soil available water capacity. Drainage during cash crop growth represented a mean of 15-30% or 25-35% of the total drainage of the crop succession for the rainfed or irrigated crop, respectively (Table 3). Even with a low SNC at initialisation, nitrate leaching varied greatly among sites as drainage varied. Evapotranspiration during the cash crop period represented 40% or 30% of total evapotranspiration over the crop succession when the cash crop was dry or irrigated, respectively.

SWC on April 15, just before spring crop sowing, depended on climate and soil available water capacity. For all five sites, SWC represented a mean of 91-95% of total available water capacity. SWC in the seedbed was ca. 80% of the SWC at field capacity, but varied among sites due to differences in spring rainfall. Sites with high drainage, such as LAL and RDL, had lower SNC on April 15 than the other sites.

Maize grain yield ranged from 7.6-13.3 Mg ha^{-1} among sites, while sunflower yield ranged from 0.4-3.7 Mg ha^{-1}, which agrees with the ranges of yields measured under farming conditions. For maize, thanks to automatic irrigation, mean water stress stays above 0.84 for the minimal value (Table 3), a stress level that does not induce significant yield loss. However, the water volumes varied greatly among sites, from 130 to 307 mm in average. Conversely, moderate to strong water stress was predicted for sunflower, and the intensity varied greatly depending among sites and years. Little N stress was predicted during the vegetative phase of maize, but it was higher during its reproductive phase and during both phases for sunflower.

(Insert Table 3 around here)

3.2. Cover crop biomass at termination

Cover crop biomass varied greatly among species, and sowing and termination dates (Figure 2). The two factors that explained the most variance in biomass were cover crop species and termination date (16% each) (Table 4). Species, termination date and their interaction explained 39% of the variance. The later the cover crop was terminated, the more biomass it produced. White mustard grows rapidly, but it had the lowest biomass (0-2.6 Mg.ha^{-1}). It grew little during winter and spring, which is consistent with its genetic characteristics. The biomass of the bispecific mixture and ryegrass ranged from 0-6.5 and 0-4.3 Mg.ha^{-1}, respectively. These two types grew strongly in winter and spring, with their biomass doubling from December 15 to March 15, and often doubling again from March 15 to April 15. Conversely, vetch biomass had high heterogeneity in growth, with biomass ranging from 0 (no emergence due to drought) to 6.9 Mg.ha^{-1}. Sowing date was the third factor that explained the variance of cover crop biomass at termination (48% variance explained by the three factors and their interactions).

Later sowing decreased biomass; for example, the biomass of cover crops sown on September 20 instead of August 5 was 67-75% lower.

(Insert Figure 2 around here)

Site was the last factor that explained a large percentage of the variance: species, termination and sowing dates, site and their interactions explained 60%. Cover crops grew more and with less variability at wet sites, such as LAL. For dry sites, cover crops did not grow as well in certain years due to the influence of strong water stress on emergence and/or growth, which resulted in biomass less than 0.5 Mg ha^{-1}. The influence of water stress was also related to species; for example, mustard was generally more sensitive to water stress than ryegrass.

3.3. Changes in water and N balance during the crop succession

3.3.1. Cover crop evapotranspiration, drainage and nitrate leaching

Cover crops increased evapotranspiration by a mean of 15-60 mm during the fallow period due to plant transpiration, depending on the cover crop management practice. Termination date, residue management, species, sowing date, site and their interactions explained only 31% of the variance in evapotranspiration difference. The most influential explanatory factor was termination date (7%): the later a cover crop was terminated, the greater the difference in evapotranspiration with bare soil (Table 3), highlighting the greater water consumption due to cover crop growth. Residue management also explained approximately the same level of variance in evapotranspiration well, with a lower increase in evapotranspiration because mulch decreased evaporation. When cover crops were terminated on November 15, evapotranspiration of the two residue-management practices differed by ca. 30 mm, but this difference decreased with later termination dates (Figure S1). Cover crop species was the third most influential factor that explained the variance, 4% alone and 26% combined with the previous ones. For example, white mustard, with relatively low biomass, increased evapotranspiration less than vetch or ryegrass, which grew for a longer period. The spring regrowth of ryegrass and the bispecific mixture increased evapotranspiration strongly. Site and sowing date explained the variance only slightly.

Cover crops decreased water drainage by a mean of 5-40 mm, mainly during the fallow period, depending on the site. This decrease depended mainly on the sowing and termination dates, which explained 13% and 7% of the total variance, respectively. For all treatments at each site, earlier sowing and later termination decreased water drainage due to the increase in the duration of the cover crop growing season (Figure S2). The site explained 5% of the variance, while species explained only 2%: a slightly larger decrease in drainage was predicted for the bispecific mixture and Italian ryegrass. Sowing and termination dates, site, species and their interactions explained 38% of the variance in drainage compared to bare soil in the fallow period.

Cover crops decreased nitrate leaching mainly during the fallow period, but the decrease varied greatly depending on the soil and climate of the site. Site alone explained 65% of the variance in the decrease. Sites with the highest nitrate leaching under bare soil conditions (LAL and RDL) had the largest decrease in nitrate leaching: 15-45 kg N.ha^{-1} per year. The other sites, with lower nitrate leaching with bare soil, had a smaller decrease: ca. 10 kg N.ha^{-1} at AUZ, and 5 kg N.ha^{-1} or less at LEC and PEY (Figure S3). Thus, the three factors that explained the most variance were, in descending order, sowing date, species and termination date but with very little variance explained (4%, 1% and 1% respectively). As expected, the later the sowing date and the earlier the termination date, the less nitrate leaching decreased. For species, the bispecific mixture and ryegrass had a larger green manure effect than vetch. Site, sowing and termination dates, species and their interactions explained 77% of the variance during the fallow period.

3.3.2. Soil mineral N, total and seedbed soil water content at sowing the succeeding crop

Under most conditions, cover crops modified the SNC of the entire 0.9m profile on April 15, depending mainly on the site that explained 30% of the variance (Table 4). The difference with bare soil ranged from -40 to -5 kg N.ha^{-1} for the three driest sites, usually -20 to -5 kg N.ha^{-1} for LAL (+5 kg N.ha^{-1} in some cases), and -10 to +5 kg N.ha^{-1} for RDL, the rainiest site (Figure S4). Termination date explained 16% of the variance, with later dates resulting in lower SNC than that after bare soil. The decrease was 2-3 times as large for the April than for the November termination. Species explained 13% of the variance; legumes and the bispecific mixture decreased SNC less than mustard or ryegrass.

Cover crops decreased the SWC of the entire 0.9 m profile on April 15 by a mean of 0-30 mm. Termination date explained most of the variance but not much with only 13%, and later termination resulted in a greater decrease. SWC decreased for the April termination date for all sites, and for the March termination date for the three driest sites (AUZ, LEC and PEY). Explained variance increased to 38% when adding site and species as well. Decreases in SWC were due mainly to sowing ryegrass or the bispecific mixture. White mustard and vetch had little influence on SWC on April 15. The site effect highlighted differences in spring rainfall between wet and dry sites. For wet sites, even for late termination of ryegrass or the bispecific mixture, SWC decreased less than 5 mm, while for drier sites, SWC decreased by 15-40 mm (Figure S5).

Introducing cover crops into cropping systems during the fallow period influenced SWC little in the seedbed on April 15, as it depended mainly on rainfall during the previous days. For all sites, leaving cover crop residues on the soil surface increased it slightly, by a mean of 0-2% (Figure S6). The increase was higher as termination date increased, except for the last date, for which water consumption by the cover crop could decrease SWC in the seedbed. Residue management, termination date, species, site, sowing date and their interactions explained only 23% of the variance (Table 3).

(Insert Table 3 around here)

3.4. Influence on the succeeding cash crop

3.4.1. Nitrogen uptake by the succeeding cash crop

The difference in N uptake by the succeeding cash crop compared to bare soil depended on the cover crop species and termination date (Figure 3). Generally, the later the termination date, the lower was the predicted N uptake. The effect also depended on the cover crop species, vetch, the only legume, leading to higher N uptake than after bare soil in most cases. The three others tend to decreases N uptake, particularly when terminated late. Compared to bare soil, mustard decreased N uptake of the two cash crops by less than 10 kg.ha^{-1}. For ryegrass and the bispecific mixture, the decrease depended on the termination date: less than 10, ca. 25 and 40 kg.ha^{-1} for early (November-December), March and April termination, respectively. After vetch, maize took up ca. 15 kg N.ha^{-1}, regardless of the termination date. Conversely, after sunflower the difference with bare soil ranged from +5 kg/ha to -10 kg/ha.

(Insert Figure 3 around here)

3.4.2. Maize yield and irrigation amounts

The maize yield ranged from -35% to +15%, and in most cases decreased by up to 20%. The decrease in yield was due mainly to an increase in the N stress index during the vegetative phase of maize (Figure 4a). As expected, due to automatic irrigation, maize experienced little or no water stress during the vegetative and reproductive phases whatever the fallow period management (Table 3 & Figure 4ab). However, most simulations did not result in an increase in irrigation volume, which agrees with the small influence of cover crops on SWC. The few cases in which irrigation volume increased (to 30 mm) occurred after terminating ryegrass and the bispecific mixture on April 15. This phenomenon occurred at dry sites in the few years that had a severe drought in spring. Water and N stress occurred mainly after ryegrass or the bispecific mixture, while yield increased mainly after vetch. The correlation between a decrease in yield and increase in N stress was high with R^2 equal to 0.88 and 0.83 for the vegetative and reproductive phase, respectively, while no correlation was predicted between decreased yield and water stress.

(Insert Figure 4 around here)

3.4.3. Rainfed sunflower yield

The change in sunflower yield ranged from -40 to +20%, with a mean decrease of 10% for all types of cover crop species and management practices (Figure 5). During the vegetative phase, N stress increased slightly but water stress increased greatly in spring with April termination of ryegrass and the bispecific mixture in dry years, especially in 1996, 2010 and 2016. For dry sites (AUZ, LEC and PEY), termination on March 15 with low spring rainfall decreased yield. During the reproductive phase, most large decreases in yield were due to N stress after ryegrass or the bispecific mixture with termination date at March 15 or April 15. Sunflower yield increased mainly after vetch and, to a lesser extent, the bispecific mixture, as for maize. Correlations between the decrease in yield and increase in N stress were significant, with R^2 equal 0.52 and 0.51 for the vegetative and reproductive phase, respectively. Like for maize, and despite the absence of irrigation, there was little or no correlation between a decrease in yield and changes in water stress due to cover crops ($R^2 \approx 0.00$ and 0.27 in the vegetative and reproductive phase, respectively).

(Insert Figure 5 around here)

4. Discussion

4.1. Cover crops decreased nitrate leaching and drainage as a function of their sowing date

The simulations indicate that cover crops decreased nitrate leaching effectively during the fallow period compared to bare soil and were less effective with legume than with non-legume species, as experiments and other simulation studies have shown (Constantin et al., 2010; Tonitto et al., 2006; Tribouillois et al., 2015a). As cover crop biomass and N uptake depend greatly on sowing and termination dates along with climate conditions, the sowing date is crucial for optimal growth in autumn and to decrease nitrate leaching effectively (Constantin et al., 2015a). For instance, late sowing does not allow for optimal growth of cover crops due to low temperatures and solar radiation, which are reinforced by a dry autumn (Bodner et al., 2010). Sowing date also has a strong influence on decreasing water drainage. The earlier the cover crop is sown, the larger the decrease in water drainage, as shown in a previous study in this region (e.g. Meyer et al., 2020).

Termination date also influenced the production of cover crop biomass, which also depended on the species. In a dry autumn, late sowing of vetch can limit its growth strongly. Species with rapid growth in summer and a short crop cycle, such as white mustard, stop growing in late autumn/early winter, when they reach senescence (Bodner et al., 2007). Conversely, species such as ryegrass have a strong ability to resume growth in spring, and their biomass can double or triple in a few weeks in spring. White mustard, with relatively low biomass, increased evapotranspiration less than vetch or ryegrass, which grew for a longer period. The spring regrowth of ryegrass and the bispecific mixture increased evapotranspiration strongly. This kind of growth had the greatest influence on the water balance in the present study, with the largest decrease in drainage when the cover crop was terminated in April. Although drainage varied greatly among sites (by a mean of 100 to more than 600 mm), the decrease due to cover crops varied little among them. Unlike the decrease in nitrate leaching, which was similar to that under bare soil, the decrease in drainage could represent a small or large percentage of total drainage. Consequently, the influence of cover crops on drainage could be limited through management choices at sites with low annual drainage. Management practices should be adapted in certain cases to decrease biomass production in order to decrease cover crop evapotranspiration and the decrease in drainage (Nielsen et al., 2015; Tribouillois et al., 2018).

4.2. Cover crops decreased total SWC but did not influence seedbed SWC

Termination dates are crucial for determining the influence of cover crops on the amount of water available in the soil profile for the succeeding crop. Several studies highlighted the risk of lower SWC at sowing of the succeeding cash crop (Mitchell et al., 2015; Unger and Vigil, 1998). When SWC decreased, particularly at dry sites with late cover crop termination and strong growth in spring, no influence on the seedbed SWC was predicted, as rainfall on days before sowing was sufficient to refill this soil layer. However, when cover crops were terminated the same day the cash crop was sown, as in conservation agriculture, seedbed SWC could be lower, especially under dry spring conditions. Lower SWC could thus induce late emergence and delay development of the succeeding cash crop. We observed similar results in a previous experimental study conducted under similar soil-climate conditions, during which the SWC in the upper 0.2 m of soil in April did not differ significantly between bare soil and cover crops (Meyer et al., 2020). This could be due to the frequent rewetting of the upper soil layers with spring rainfall that does not saturate the soil, but wets the surface sufficiently to provide homogeneous conditions for sowing the cash crop and thus avoids water stress at emergence.

4.3. Cover crops induced mainly N stress, sometimes decreasing cash crop yield

Cover crops have a well-documented influence on succeeding crop yields. Increased maize yields have been reported, particularly with legume cover crops such as vetch (Clark et al., 1997). We also predicted increased maize and sunflower yields after vetch in the present study. This increase is due to the additional supply of mineral N after decomposition of legume residues, which are richer in N due to symbiotic N_2 fixation and the green manure effect of these legumes (Tosti et al., 2014; Tribouillois et al., 2015b). Conversely, sowing a non-legume cover crop during the fallow period can result in mineral N pre-emption, which is detrimental to the growth of the succeeding cash crop when doses of N fertiliser are not increased (Alvarez et al., 2017). In the present study, decreases in SNC were predicted as a function of the termination date and cover crop species. A late termination date could induce a larger decrease in SNC. We predicted a decrease in maize and sunflower yields under certain conditions, which was explained mainly by N stress but also by water stress in specific cases. Maize experienced water stress in spring 2011 during the vegetative phase, despite automatic irrigation, which did not increase due to cover crops. Severe drought and high temperatures in April and May 2011 explained this high stress, which strongly decreased yield. Except for a few cases, the succeeding cash crop suffered mainly from N stress and pre-emptive competition from cover crops, resulting in a decrease in yield (by 0.5-3.0 $Mg.ha^{-1}$), especially for late spring termination. Marcillo and Miguez (2017) reported the importance of adapting the cover crop termination date to avoid a decrease in yield due to lower SNC. We also predicted the largest decrease in yield with the latest termination date (the day before sowing the cash crop), due to a phase of net N organisation after incorporating cover crop residues. This influence was greater for cover crops with strong growth in spring, resulting in lower SNC. For sunflower, grown under dry conditions, we also predicted a decrease in yield due to water and N stress. However, as mentioned, sowing vetch, regardless of its termination date, or mustard, which stops growing in winter, or autumn termination of ryegrass, can avoid the decrease in yield of the succeeding cash crop.

Sowing a legume cover crop increases the yield of the succeeding cash crop as it avoids N stress due to pre-emptive competition (Tonitto et al., 2006). However, legume cover crops increased the risk of nitrate leaching compared to that with non-legumes, as they take up less N from the soil due to symbiotic N_2 fixation (Thorup-Kristensen and Nielsen, 1998). Nevertheless, sowing legumes remains more effective than bare soil and could be beneficial, especially for sites with low nitrate leaching, to promote the green manure effect and thus use less N fertiliser. Combining legumes and non-legumes could be an interesting compromise as this type of mixture has performed well for the management of mineral N, to significantly decrease leaching and increase the green manure effect (Tosti et al., 2014, 2012; Tribouillois et al., 2015a). Cover crop mixtures that include legumes and non-legumes, along with adapted management (i.e. species, sowing and termination dates), could be an effective solution to provide several ecosystem services depending on the specific objectives and a site's soil and climate, especially to avoid water problems (White et al., 2017). In zones prone to nitrate leaching, farmers should sow more legume/non-legume mixtures and limit the use of pure legumes during fallow periods. In dry regions, late termination of grass cover crops, such as ryegrass, is strongly discouraged to avoid the risk of mineral N and water pre-emptions which decrease the yield of the succeeding cash crop (Alonso-Ayuso et al., 2014).

4.4. Study boundaries and extrapolation in space and time

Using STICS, we assumed that physical soil properties, such as bulk density and soil infiltration capacity, remained constant throughout the crop succession, with or without cover crops. However, on bare soil, a crust can form on the soil surface that decreases water infiltration. Sowing cover crops during the fallow period changes the physical properties of the soil and increases the proportion of water that infiltrates (Basche and DeLonge, 2019; Yu et al., 2016). This could result in greater drainage volume with cover crops than that predicted by STICS, especially when fields slope, which could induce runoff. Studies also suggest that cover crops change soil bulk density to increase the soil water reserve slightly (de Lima et al., 2012; Strudley et al., 2008). In addition, soil decompaction increases the depth of soil explored by roots of the succeeding cash crop (Chen et al., 2014; Chen and Weil, 2011).

Nevertheless, changes in soil structure due to changes in pore distribution and size can increase the reservoir size over the long term. Gabriel et al (2019) showed that changes in soil physical properties, an increase in reservoir size and increased hydraulic continuity would partially compensate for water losses due to transpiration of cover crops compared to bare soil. As our study focused on the succession of a cover crop and a short-term cash crop, we assumed that the increase in water infiltration in the soil and the size of the reservoir due to cover crops was negligible. We simulated all sites using a soil depth of 0.9 m, and simulating deeper or shallower soils could broaden results for crop water or N stress. In a shallower soil, with a lower water-retention capacity and more rapid nitrate leaching, stress of the succeeding cash crop could increase. In a deeper soil, the stress could decrease, as roots can grow more deeply and access more water and abiotic resources.

The present study highlighted the influence of termination date on evapotranspiration, water drainage and soil water and mineral N availability for the succeeding cash crop, confirming the results obtained by Alonso-Ayuso et al. (2018). Residue management after termination also modified the influence of cover crops on the soil water balance. Stopping growth and leaving cover crop residues on the soil surface limits the increase in evapotranspiration caused by the decrease in soil evaporation compared to mouldboard ploughing (Gabriel et al., 2019). This difference in evapotranspiration can increase surface SWC, as several studies show for the upper 0.2 m of soil (Moschler et al., 1967; Stipešević and Kladivko, 2005).

Considering other locations, these results are valid in similar climate conditions with temperate climate and dry summers. We simulated a range of sites with contrasted annual precipitation and potential evapotranspiration and a large range of cover crops species and management. It gave some trends on the potential impact of cover crops on several water and N components depending on termination date, presence of legumes or strong regrowth at spring for temperate climate such as in Europe or USA. Since we also gave the interaction between the different factors among which is the site, one can extrapolate the results more easily, particularly if the site does not influence the results. They should however be careful in to different conditions and run the scenario again within the new pedoclimatic context.

In climate change context, cover crops are an interesting tool to overcome some crucial issues by reducing efficiently nitrate leaching avoiding indirect N_2O emissions in aquifers. Some studies have shown that this efficiency remains in climate change context as well (Alonso-Ayuso et al., 2018; Tribouillois et al., 2018). Cover crops also increase C storage in soil and enhance the green gashouse emissions balance over the long term, contributing to mitigate climate change effect (Launay et al., 2021; Tribouillois et al., 2018). However two main possible drawbacks should be point out, particularly in dry region with climate change: the reduction of drainage could increase with higher biomass production of cover crops and pre-emptive competition for water and N for the following crop could worsen, as suggested by Alonso-Ayuso et al. (2018). According to these authors and our results, adapting the termination date of the cover crops with earlier termination should allow to avoid or limit these effects and still reduce N and GHG pollution.

5. Conclusion

Our study highlights relevant interactions between soil, climate, choice of cover crop species and its management, including sowing and termination dates and residue management after termination. Cover crops decrease nitrate leaching effectively but also decrease drainage by increasing evapotranspiration during the fallow period and crop succession in the climate conditions of the Adour-Garonne catchment. The extent of this influence depends on the amount of biomass cover crop produces, indicating that adapted management could control the negative effects. In areas with low drainage in winter and little rainfall in spring, late spring termination of a cover crop could result in high water and mineral N pre-emption before sowing of the succeeding cash crop, thus decreasing its yield, mainly via N stress. Well-managed cover crops could limit or preclude water and N stress for the succeeding cash crop and its yield (i.e. late termination should be avoided in dry climates). Sowing legume cover crops is clearly beneficial for yield due to the green manure effect. However, their use must be adapted to the risk of nitrate leaching to be mitigated in areas with high water drainage. Bispecific mixtures could be a useful compromise to limit nitrate leaching and promote green manure effects. Nevertheless, they should be adapted to decrease their influence on the water balance by adapting the date of termination, particularly in dry climates, where quantitative water management is an issue and can worsen with climate change. Finally, cover crop management should be optimised locally depending on the ecosystem services and issues targeted, and this could be done via decision-making tools using a soil-crop model.

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Conflict of interest

The authors declare that they have no conflict of interest.

Acknowledgments

This study was funded by the Adour-Garonne water agency (BAGAGES project) and the Occitanie Region (CLE BAGAGES-Cisol project). We thank Michelle and Michael Corson for proofreading and correcting the English. The authors would like to extend great thanks to Julie Bréchemier and Maylis Lachaussée for soil sampling across the Adour-Garonne catchment.

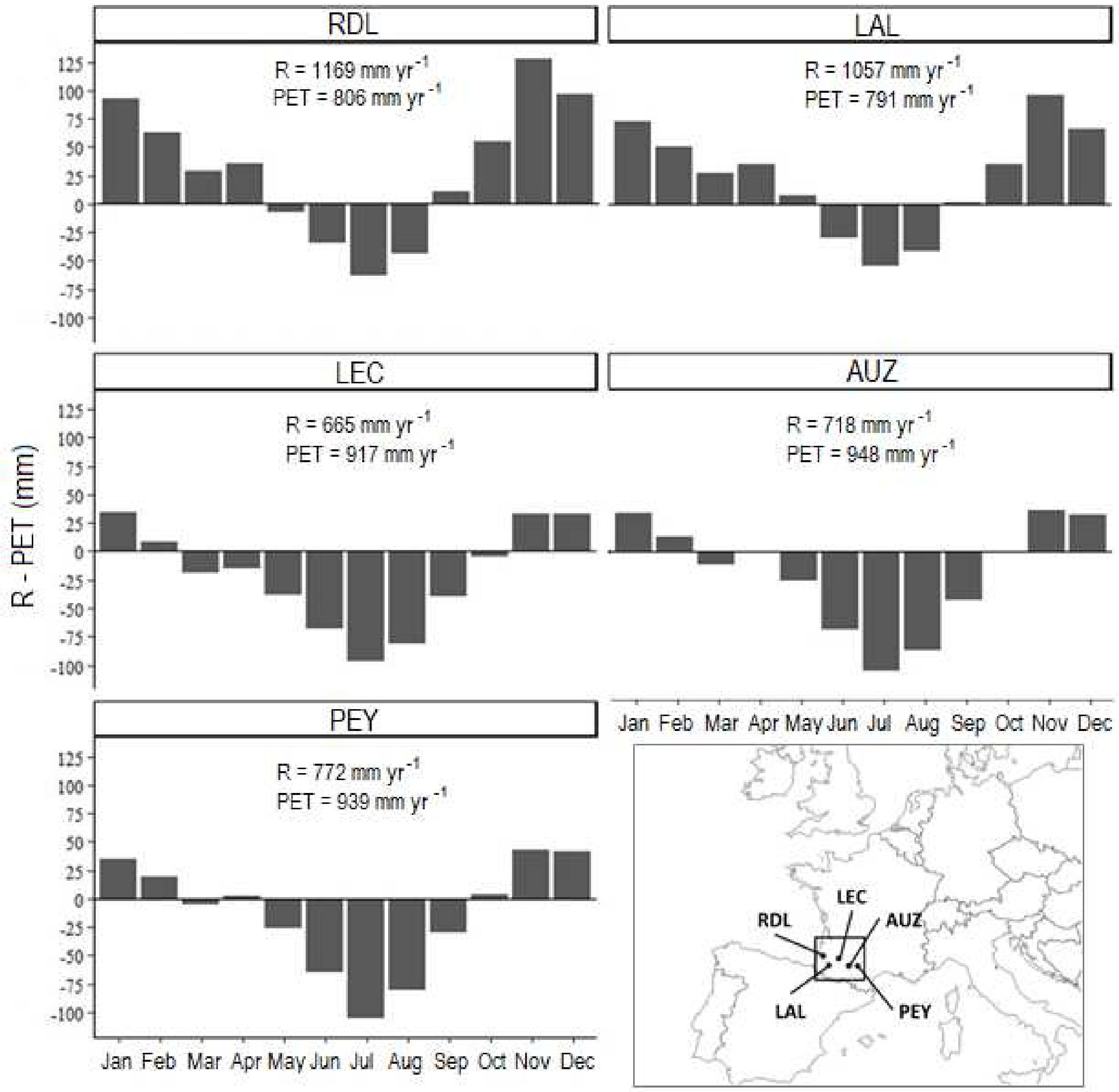

Figure 1. Monthly mean difference between rainfall (R) and potential evapotranspiration (PET) from 1990-2017 for each site in the study area.

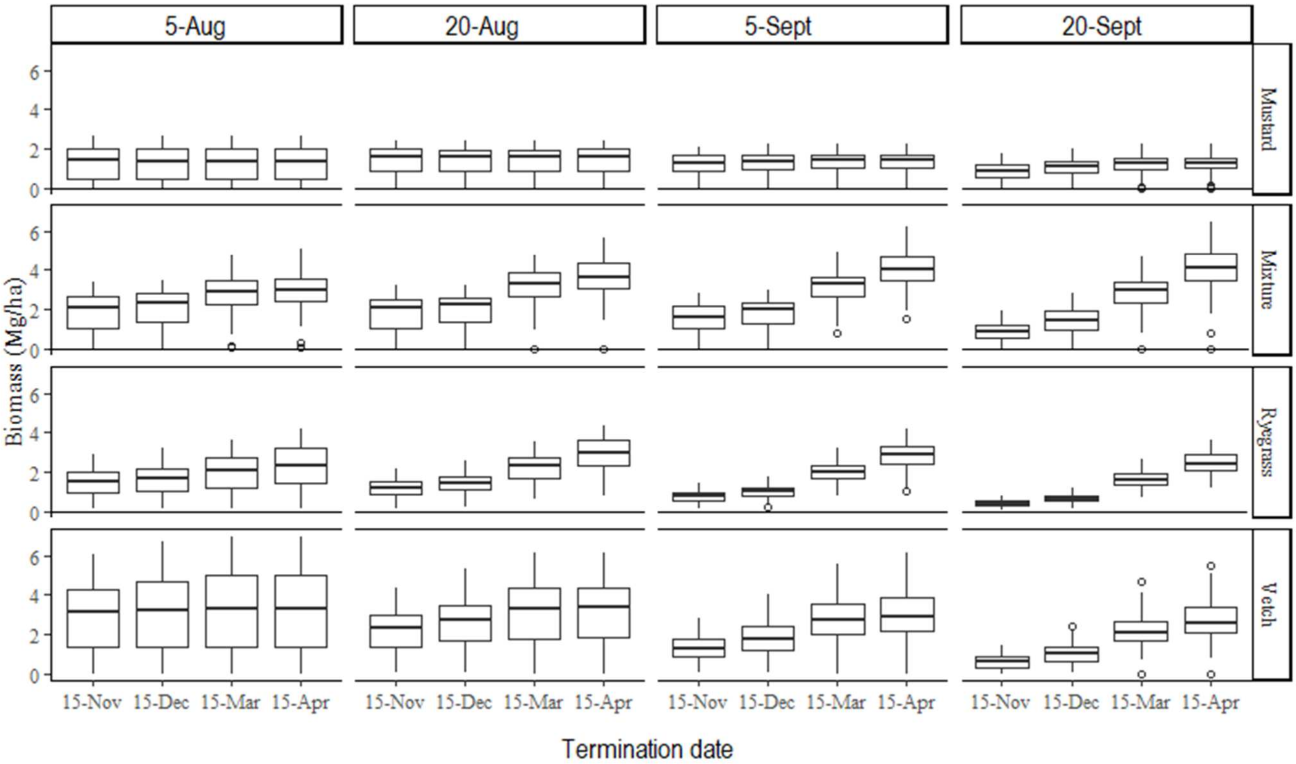

Figure 2. Boxplots of final cover crop biomass by the three main factors explaining its variance: species, termination and sowing date, all sites gather.

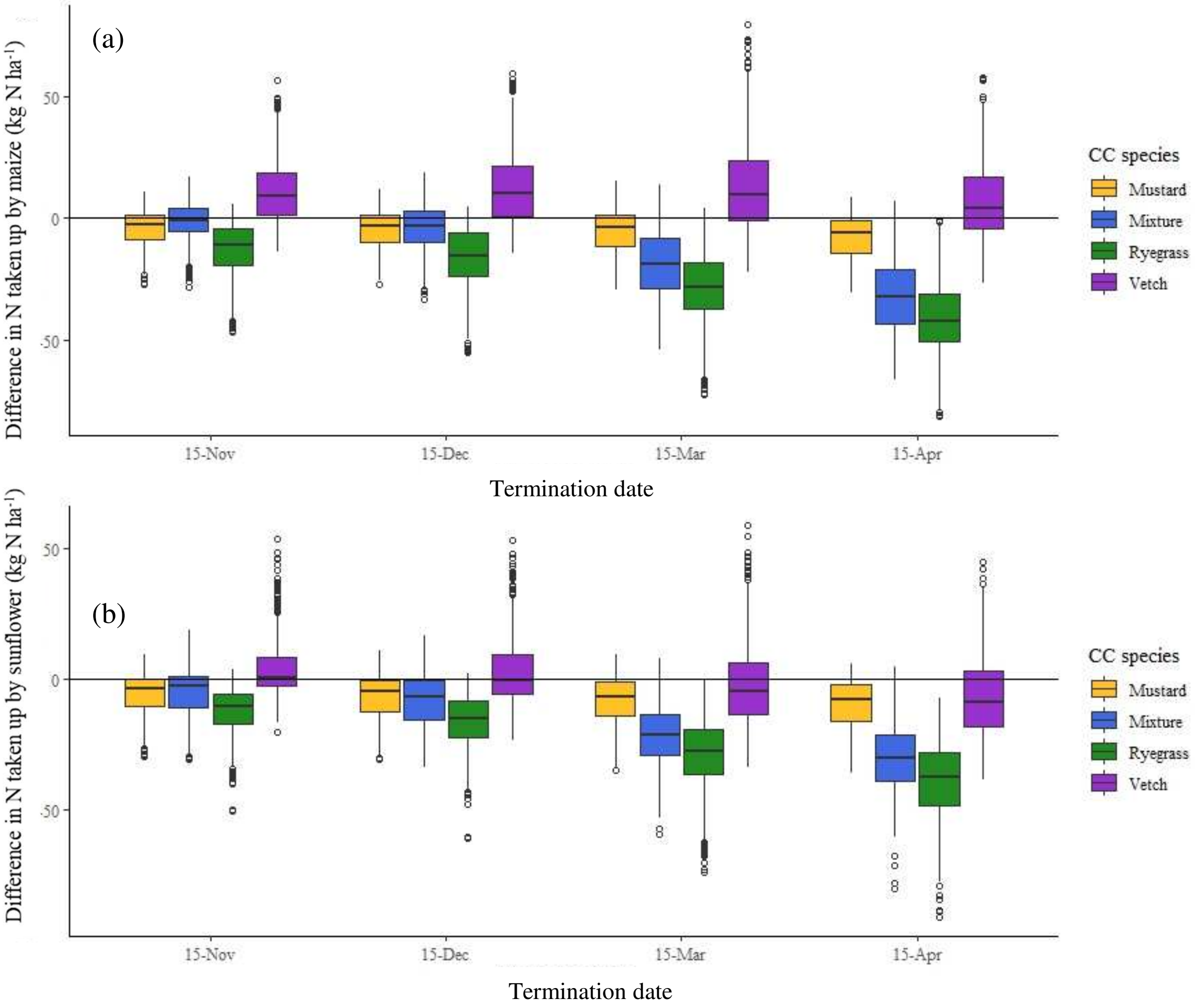

Figure 3. Difference in (a) maize and (b) sunflower nitrogen (N) uptake as a function of the previous cover crop (CC) compared to that with bare soil. Mixture represents a mixture of Ethiopian mustard and red clover. Error bars indicate 1.5 times the interquartile range. Values above 0 means that the succeeding cash crop has uptake more N after the given CC than after a bare soil during the fallow period. Values below 0 means the opposite.

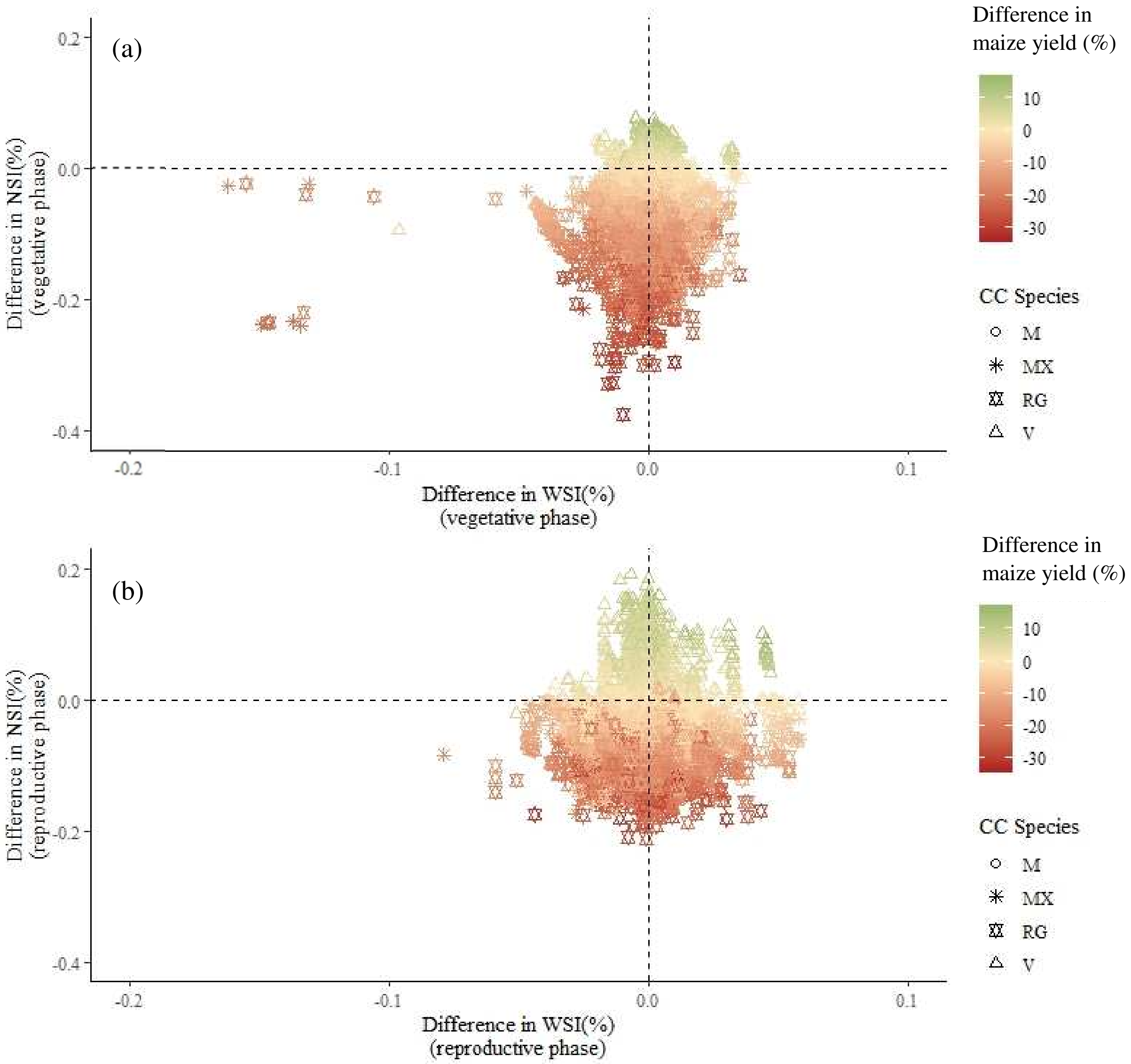

Figure 4. Difference in the water stress index (WSI) and nitrogen stress index (NSI) due to a cover crop in (a) vegetative and (b) reproductive phases of the following irrigated maize and the influence on yield (in colour) compared to a bare soil fallow period. Cover crop (CC) species were white mustard (M), a bispecific mixture of Ethiopian mustard and red clover (MX), Italian ryegrass (RG) and common vetch (V). Positive values for NSI and WSI indicate lower stress with cover crops, while negative values indicate higher stress.

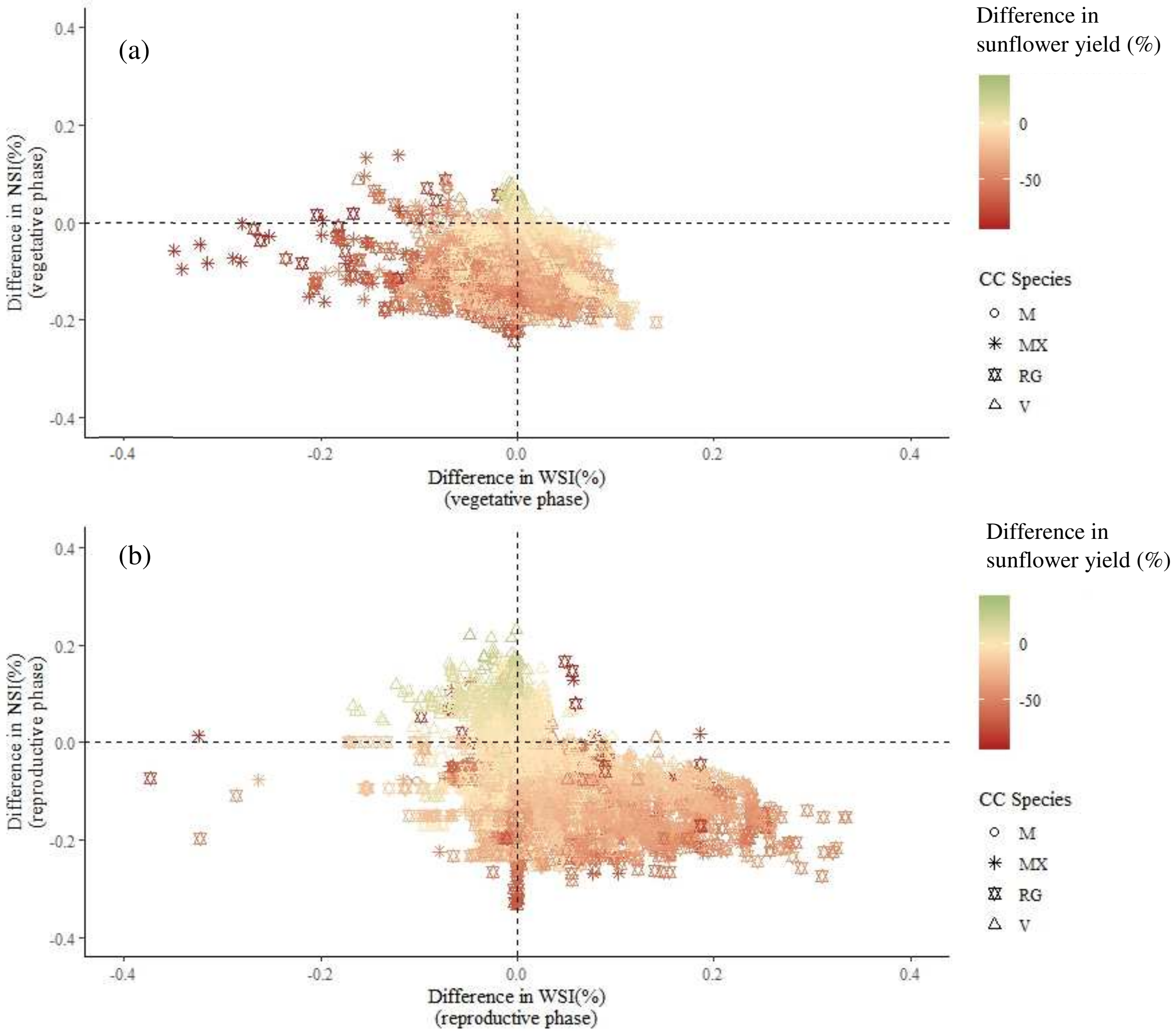

Figure 5. Difference in the water stress index (WSI) and nitrogen stress index (NSI) due to a cover crop in (a) vegetative and (b) reproductive phases of the following rainfed sunflower and the influence on yield (in colour) compared to a bare soil fallow period. Cover crop (CC) species were white mustard (M), a bispecific mixture of Ethiopian mustard and red clover (MX), Italian ryegrass (RG) and common vetch (V). Positive values for NSI and WSI indicate lower stress with cover crops, while negative values indicate higher stress.

Table 1. Data for the virtual experimental design: fallow-period management of cover crop species, date and depth of tillage; date of sowing and termination of the cover crop, residue management; cash crop species, sowing date, harvest date, irrigation and nitrogen fertilisation.

Cover crop species	• No cover crop • Italian ryegrass • White mustard • Common vetch • Mixture of red clover and Ethiopian mustard
Soil tillage date and depth	• Date of cover crop sowing to a depth of 3 cm • April 15 to a depth of 10 cm
Cover crop sowing date	• August 5 • August 20 • September 5 • September 20
Cover crop termination date	• November 15 • December 15 • March 15 • April 15
Cover crop residue management	• Mulch left on the soil surface • Ploughed
Cash crop sowing date	April 16
Cash crop harvest date	• Maize: November 20 • Sunflower: October 16
Cash crop irrigation	• Maize: irrigated at 85% of requirements • Sunflower: rainfed
Cash crop nitrogen supply	• Maize: 45 and 145 kg N ha^{-1} on April 18 and June 4, respectively • Sunflower: 50 kg N ha^{-1} on April 30

Table 2. Soil properties of the five sites of the study area.

Site	RDL	LAL	LEC	AUZ	PEY
Latitude	43°55’ N	43°29’ N	43°56’ N	43°30’ N	43°42’ N
Longitude	0°55’ W	0°19’ W	0°37’ E	1°29’ E	2°12’ E
Rainfall (mm.year^{-1})	1169	1057	665	718	772
Soil texture	Sand	Silt loam	Silty clay	Clay loam	Clay loam
Depth (m)	0.9	0.9	0.9	0.9	0.9
Clay content from 0-0.25 m (%)	4.3	15.5	45.3	30.6	34.9
Bulk density (g.cm^{-3})	1.35	1.45	1.50	1.48	1.40
Soil water content at field capacity (mm)	98	278	392	243	403
Soil water content at wilting point (mm)	36	131	243	137	239
Soil available water capacity (mm)	62	147	149	106	164

Table 3. Main results for soil water and nitrogen content and main crop balances of the control scenario with bare soil for the 5 sites: RDL, LAL, LEC, AUZ and PEY. For each site, the minimum, mean and maximum of each variable during the fallow period, during crop succession and for the cash crop is shown. The nitrogen stress index (NSI) and water stress index (WSI) range from 0-1; the lower the index, the greater the stress. According to bibliography, we can consider that maize yield is affected when stress level are below 0.85 for nitrogen and 0.80 for water while they are 0.80 and 0.60 for sunflower (Debaeke et al., 2012; García-López et al., 2016; Mueller and Vyn, 2018; Orta et al., 2002; Zhao et al., 2018).

Site	**RDL**			**LAL**			**LEC**			**AUZ**			**PEY**		
	min	mean	max	min	mean	max	min	mean	max	min	mean	max	min	mean	max
Fallow period, form August 1st to April 15th															
Drainage (mm)	244	625	1223	130	433	751	0	90	422	0	130	353	0	115	384
Evapotranspiration (mm)	225	261	293	258	300	327	216	291	358	254	294	338	242	315	369
Nitrate leaching (kgN ha^{-1})	36	57	72	11	36	48	0	6	25	0	15	35	0	8	28
Crop succession: bare soil + maize															
Drainage (mm)	516	931	1429	212	571	1003	0	120	471	0	199	442	0	173	454
Evapotranspiration (mm)	734	813	875	792	890	978	736	947	1085	870	980	1111	906	1011	1124
Nitrate leaching (kgN ha^{-1})	52	90	167	20	44	85	0	7	26	0	22	57	0	12	33
Crop succession: bare soil + sunflower															
Drainage (mm)	349	787	1302	191	514	884	0	105	430	0	164	353	0	150	425
Evapotranspiration (mm)	501	608	669	707	771	848	648	735	846	649	718	815	726	809	925
Nitrate leaching (kgN ha^{-1})	49	79	113	18	42	74	0	7	26	0	19	48	0	10	31
April 15th, at the cash crop sowing date															
Soil N mineral content (kg.ha^{-1})	5	12	16	18	24	41	24	39	50	20	35	56	25	41	57
Soil water content (mm)	74	91	98	252	271	278	241	358	392	194	232	243	234	377	403
Soil water content from 0-10 cm (%)	1	6	8	5	17	20	16	25	29	5	14	18	20	27	32
Next cash crop: maize															
Yields (Mg.ha^{-1})	7.6	10.3	12.6	8.2	10.8	12.6	7.7	10.2	12.0	8.0	10.9	13.3	8.0	11.1	13.1
Irrigation supply (mm)	75	232	326	0	130	270	30	248	390	150	307	450	60	248	420
NSI $_{\text{vegetative phase}}$	0.85	0.97	1.00	0.90	0.97	1.00	0.89	0.95	1.00	0.94	0.97	1.00	0.87	0.95	0.99
NSI $_{\text{reproductive phase}}$	0.62	0.78	0.89	0.68	0.78	0.86	0.72	0.79	0.85	0.71	0.79	0.88	0.73	0.79	0.88
WSI $_{\text{vegetative phase}}$	0.84	0.92	0.96	0.96	0.99	1.00	0.95	0.98	1.00	0.95	0.97	0.99	0.93	0.98	1.00
WSI $_{\text{reproductive phase}}$	0.87	0.95	0.98	0.94	0.97	1.00	0.91	0.95	1.00	0.92	0.95	0.99	0.90	0.95	0.99
Next cash crop: sunflower															
Yields (Mg.ha^{-1})	0.8	1.6	2.9	1.2	2.7	3.7	0.4	1.9	3.5	0.8	1.3	2.6	0.9	1.9	3.5
NSI $_{\text{vegetative phase}}$	0.58	0.64	0.72	0.57	0.64	0.70	0.49	0.58	0.69	0.47	0.57	0.66	0.47	0.58	0.69
NSI $_{\text{reproductive phase}}$	0.40	0.55	0.67	0.34	0.53	0.69	0.33	0.46	0.64	0.30	0.45	0.57	0.31	0.46	0.56
WSI $_{\text{vegetative phase}}$	0.63	0.77	0.96	0.80	0.96	1.00	0.54	0.85	1.00	0.61	0.75	0.93	0.62	0.87	1.00
WSI $_{\text{reproductive phase}}$	0.62	0.88	1.00	0.58	0.84	1.00	0.64	0.83	1.00	0.69	0.87	1.00	0.60	0.81	1.00

Table 4. Explained variance (EV) of the model output of interest by the explanatory factors (in descending order from left to right) and their interactions (*F*×*F*). Termination = termination date, Sowing = sowing date, Residues = residue management (ploughed or left on the surface).

	Factor 1	EV (%)	Factor 2	EV (%)	EV (F1×F2) (%)	Factor 3	EV (%)	EV (F1×F2×F3) (%)	Factor 4	EV (%)	EV (F1×F2×F3×F4) (%)	Total EV (%)
Final cover crop biomass	Species	16	Termination	16	39	Sowing	6	48	Site	3	60	60
Difference compared to bare soil during the fallow period												
Evapotranspiration	Termination	7	Residues	7	17	Species	4	26	Sowing	2	29	31
Drainage	Sowing	13	Termination	7	20	Site	5	27	Species	2	33	38
Nitrate leaching	Site	65	Sowing	4	72	Species	1	74	Termination	1	77	77
Difference compared to bare soil on April 15												
Soil mineral N	Site	30	Termination	16	47	Species	13	63	Sowing	0	68	70
Soil water content	Termination	13	Species	5	25	Site	7	38	Sowing	1	43	45
Soil water content from 0-0.1 m	Residues	6	Termination	2	13	Species	1	17	Site	1	20	23