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

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8 **Key words**

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

10 **Highlights**

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

15 **Abstract**

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

41 **1. Introduction**

42 Cover crops, also called catch crops or green manure, are one of the pillars of agroecological practices
43 and are essential for diversifying cropping systems (Duru et al., 2015). Sown during the fallow period
44 between two annual cash crops and usually terminated long or immediately before sowing the
45 succeeding cash crop, they are returned to the soil. Cover crops can provide a wide range of ecosystem
46 services, such as provision of a green manure effect; storage of carbon in the soil; reduction of nitrate
47 leaching and erosion, a better greenhouse gas balance and weed control (Constantin et al., 2010; Ryder
48 and Fares, 2008; Schipanski et al., 2014; Tonitto et al., 2006; Tosti et al., 2014; Tribouillois et al., 2018).
49 As cover crops increase evapotranspiration during the fallow period compared to bare soil (Unger and
50 Vigil, 1998) and take up mineral nitrogen (N) from the soil, they change water and N balances during
51 and following this period. Cover crops generally decrease drainage (Meyer et al., 2019) and can decrease
52 soil water content (SWC) before sowing of the succeeding crop, particularly when they are terminated
53 immediately before sowing (i.e. “late termination”) (Meyer et al., 2020). The increase in water and
54 mineral N uptake can decrease water and N availability for the succeeding crop, and this pre-emptive
55 competition occurs particularly in dry regions (Thorup-Kristensen et al., 2003). In the context of climate
56 change, with temperatures and lower rainfall in arid and temperate regions (IPCC, 2013), sowing cover
57 crops during the fallow period could increase issues for groundwater recharge and decrease yield of the
58 succeeding cash crop, by reducing drainage (Tribouillois et al., 2018) and soil water and N availability
59 for the following crop (Alonso-Ayuso et al., 2018; Meyer et al., 2020).

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

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

72 Thus, cover crop management is crucial to avoid or limit the cover crop's potential negative influence
73 on the succeeding crop. Management practices should be adapted locally to a site, its soil and climate
74 characteristics, and the succession of cash crops, which determine the degree of potential pre-emptive
75 competition. Crop models can be a valuable tool to assess the influence of cover crops on water and N
76 balances under multiple cropping system management practices, particularly over large areas (Bergez
77 et al., 2010). The objective of the present study was to quantify the influence of cover crop management
78 scenarios on water and N balances and on the succeeding cash crop in multiple soils and climates at the
79 regional scale. The study was conducted for the Adour-Garonne catchment (120 000 km²), a large
80 catchment in south-western France which has frequent water deficit in aquifers during summer and
81 irrigation restriction (Mazzega et al., 2014), using the STICS soil-crop model (Brisson et al., 2009,
82 2003).

83

84 **2. Materials and methods**

85 **2.1. Study area**

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

94 2.2. Virtual experimental design

95 The simulation approach consisted of using the STICS soil-crop model (Brisson et al., 1998; 2002; 2003;
96 2009) to simulate the fallow period and the succeeding crop for five soil-climate combinations over 18
97 years. We tested several fallow-period management practices, including bare soil or cover crops of
98 multiple species, sowing and termination dates and cover crop residue management practices, which
99 were followed by maize or sunflower (*Helianthus annuus*) in a continuous simulation to take into
100 account the effect of cover crop residues on the cash crop. The simulation were re-initialized at each
101 beginning of the fallow period to avoid the cumulative effect of cover crops (Constantin et al., 2011).
102 For all five sites, we simulated bare soil as a control and four types of cover crops commonly sown
103 during the fallow period between a winter and spring crop: white mustard (*Sinapis alba*), common vetch
104 (*Vicia sativa*), Italian ryegrass (*Lolium multiflorum*) and a bispecific mixture of red clover (*Trifolium*
105 *incarnatum*) and Ethiopian mustard (*Brassica carinata*). These four types were selected for their
106 contrasting growth, production and potential biomass C:N ratio; variable sensitivity to water stress, high
107 temperatures and frost; and contrasting sensitivity to soil mineral N availability (i.e. legume vs. non-
108 legume).

109 We tested four cover crop sowing dates (August 5, August 20, September 5 and September 20),
110 combined with four cover crop termination dates from late autumn to early spring (November 15,
111 December 15, March 15 and April 15) (Table 1). At termination, we simulated two cover crop residue-
112 management practices: ploughed or left as mulch on the soil surface. Finally, we simulated two cash
113 crops sown on April 16: irrigated maize, with automatic irrigation triggered by the STICS model if a
114 water satisfaction index fell below 85%, and sunflower grown under rainfed conditions (without
115 irrigation). Mineral N inputs for the cash crops were determined from surveys of cropping practices in
116 the Adour-Garonne catchment. N fertilisation was 185 kg N ha⁻¹ divided into two applications for maize
117 and 50 kg N ha⁻¹ two weeks after sowing for sunflower. The simulations were conducted over 1990-
118 2017 to represent the actual climate variability of each site. For each cash crop, year and site, we ran
119 129 “species × sowing date × termination date × residue management” scenarios.

120 (Insert Table 1 around here)

121 **2.2.1. Climate and soil data**

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

131 (Insert Figure 1 around here)

132 Soil texture differed among the five sites, ranging from sandy to silty clay according to the texture
133 triangle (Jamagne et al., 1977). To match the West to East gradient with sandy to clay soils in the
134 catchment, we selected a sandy soil for RDL, silt loam for LAL, silty clay soil for LEC and clay loam
135 soils for AUZ and PEY. SWC at field capacity and permanent wilting point were estimated from texture
136 using pedotransfer functions (Table 2). For the five sites, we set soil organic N content in the upper 0.25
137 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
138 drainage.

139 (Insert Table 2 around here)

140 **2.3. Simulation methods**

141 **2.3.1. STICS model overview**

142 The STICS soil-crop model is a dynamic process-based model that runs on a daily time step. It simulates
143 crop growth and water, carbon and N balances under the influence of weather, soil and crop management
144 practices. STICS simulates cropping systems over time, from a crop cycle to a long-term succession,
145 including the management of fallow periods between cash crops. Soil water is modelled using a "tipping-
146 bucket" approach. Water demand uses a crop-coefficient approach, while N demand is based on the N

147 dilution curve, which is generic and robust (Gastal and Lemaire, 2002). Depending on the SWC and soil
148 mineral N content (SNC) in the rooting zone, water and N stresses decrease crop growth when demands
149 are not met by soil availability. When residues are left on the soil surface, the mulch decreases soil
150 evaporation as a function of the amount of biomass in the mulch. Mulch can also intercept some rainfall
151 and irrigation, and this water, retained in the mulch, evaporates according to the evaporative demand
152 (Brisson et al., 2009). STICS has been evaluated for French soil and climate contexts and for several
153 crops, including cash and cover crops (Coucheney et al., 2015). These authors classified STICS'
154 predictions as "satisfactory" to "very good" for most of the variables analysed, especially the SWC and
155 crop biomass under differing levels of N and water availability. STICS has been used to simulate cover
156 crops, in particular to predict their influence in the short to long terms on the SWC, SNC and the green
157 manure effect (Constantin et al., 2012; Tribouillois et al., 2018). Cover crop species simulated in the
158 present study were previously calibrated and validated for STICS based on several field experiments
159 (Constantin et al., 2015b; Meyer et al., 2020). The version 10 of STICS was used in this study as in
160 Meyer et al. (2020). Even if the version is different from the one used in the main paper on STICS
161 evaluation by Coucheney et al. (2015), the evolution of STICS is conducted by the STICS team with
162 automatic evaluation of the model accuracy on the same database as used in this paper. The fitting
163 obtained by the following versions of the model are checked to give similar results. The level of accuracy
164 for the different variables analysed in this paper are then still very close.

165 **2.3.2 STICS model initialisation**

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

172 **2.4. Data analysis and statistics**

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

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

189 **3. Results**

190 **3.1. Bare soil**

191 As expected, predicted drainage varied greatly among sites and was related to contrasting levels of
192 rainfall and soil available water capacity. Drainage during cash crop growth represented a mean of 15-
193 30% or 25-35% of the total drainage of the crop succession for the rainfed or irrigated crop, respectively
194 (Table 3). Even with a low SNC at initialisation, nitrate leaching varied greatly among sites as drainage
195 varied. Evapotranspiration during the cash crop period represented 40% or 30% of total
196 evapotranspiration over the crop succession when the cash crop was dry or irrigated, respectively.

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

202 Maize grain yield ranged from 7.6-13.3 Mg ha⁻¹ among sites, while sunflower yield ranged from 0.4-3.7
203 Mg ha⁻¹, which agrees with the ranges of yields measured under farming conditions. For maize, thanks
204 to automatic irrigation, mean water stress stays above 0.84 for the minimal value (Table 3), a stress level
205 that does not induce significant yield loss. However, the water volumes varied greatly among sites, from
206 130 to 307 mm in average. Conversely, moderate to strong water stress was predicted for sunflower,
207 and the intensity varied greatly depending among sites and years. Little N stress was predicted during
208 the vegetative phase of maize, but it was higher during its reproductive phase and during both phases
209 for sunflower.

210 (Insert Table 3 around here)

211 **3.2. Cover crop biomass at termination**

212 Cover crop biomass varied greatly among species, and sowing and termination dates (Figure 2). The
213 two factors that explained the most variance in biomass were cover crop species and termination date
214 (16% each) (Table 4). Species, termination date and their interaction explained 39% of the variance.
215 The later the cover crop was terminated, the more biomass it produced. White mustard grows rapidly,
216 but it had the lowest biomass (0-2.6 Mg.ha⁻¹). It grew little during winter and spring, which is consistent
217 with its genetic characteristics. The biomass of the bispecific mixture and ryegrass ranged from 0-6.5
218 and 0-4.3 Mg.ha⁻¹, respectively. These two types grew strongly in winter and spring, with their biomass
219 doubling from December 15 to March 15, and often doubling again from March 15 to April 15.
220 Conversely, vetch biomass had high heterogeneity in growth, with biomass ranging from 0 (no
221 emergence due to drought) to 6.9 Mg.ha⁻¹. Sowing date was the third factor that explained the variance
222 of cover crop biomass at termination (48% variance explained by the three factors and their interactions).

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

225 (Insert Figure 2 around here)

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

232 **3.3. Changes in water and N balance during the crop succession**

233 **3.3.1. Cover crop evapotranspiration, drainage and nitrate leaching**

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

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

256 Cover crops decreased nitrate leaching mainly during the fallow period, but the decrease varied greatly
257 depending on the soil and climate of the site. Site alone explained 65% of the variance in the decrease.
258 Sites with the highest nitrate leaching under bare soil conditions (LAL and RDL) had the largest decrease
259 in nitrate leaching: 15-45 kg N.ha⁻¹ per year. The other sites, with lower nitrate leaching with bare soil,
260 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).
261 Thus, the three factors that explained the most variance were, in descending order, sowing date, species
262 and termination date but with very little variance explained (4%, 1% and 1% respectively). As expected,
263 the later the sowing date and the earlier the termination date, the less nitrate leaching decreased. For
264 species, the bispecific mixture and ryegrass had a larger green manure effect than vetch. Site, sowing
265 and termination dates, species and their interactions explained 77% of the variance during the fallow
266 period.

267 **3.3.2. Soil mineral N, total and seedbed soil water content at sowing the succeeding crop**

268 Under most conditions, cover crops modified the SNC of the entire 0.9m profile on April 15, depending
269 mainly on the site that explained 30% of the variance (Table 4). The difference with bare soil ranged
270 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
271 some cases), and -10 to +5 kg N.ha⁻¹ for RDL, the rainiest site (Figure S4). Termination date explained
272 16% of the variance, with later dates resulting in lower SNC than that after bare soil. The decrease was
273 2-3 times as large for the April than for the November termination. Species explained 13% of the
274 variance; legumes and the bispecific mixture decreased SNC less than mustard or ryegrass.

275 Cover crops decreased the SWC of the entire 0.9 m profile on April 15 by a mean of 0-30 mm.
276 Termination date explained most of the variance but not much with only 13%, and later termination
277 resulted in a greater decrease. SWC decreased for the April termination date for all sites, and for the
278 March termination date for the three driest sites (AUZ, LEC and PEY). Explained variance increased to
279 38% when adding site and species as well. Decreases in SWC were due mainly to sowing ryegrass or
280 the bispecific mixture. White mustard and vetch had little influence on SWC on April 15. The site effect
281 highlighted differences in spring rainfall between wet and dry sites. For wet sites, even for late
282 termination of ryegrass or the bispecific mixture, SWC decreased less than 5 mm, while for drier sites,
283 SWC decreased by 15-40 mm (Figure S5).

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

290 (Insert Table 3 around here)

291 **3.4. Influence on the succeeding cash crop**

292 **3.4.1. Nitrogen uptake by the succeeding cash crop**

293 The difference in N uptake by the succeeding cash crop compared to bare soil depended on the cover
294 crop species and termination date (Figure 3). Generally, the later the termination date, the lower was the
295 predicted N uptake. The effect also depended on the cover crop species, vetch, the only legume, leading
296 to higher N uptake than after bare soil in most cases. The three others tend to decrease N uptake,
297 particularly when terminated late. Compared to bare soil, mustard decreased N uptake of the two cash
298 crops by less than 10 kg.ha⁻¹. For ryegrass and the bispecific mixture, the decrease depended on the
299 termination date: less than 10, ca. 25 and 40 kg.ha⁻¹ for early (November-December), March and April

300 termination, respectively. After vetch, maize took up ca. 15 kg N.ha⁻¹, regardless of the termination date.
301 Conversely, after sunflower the difference with bare soil ranged from +5 kg/ha to -10 kg/ha.

302 (Insert Figure 3 around here)

303 **3.4.2. Maize yield and irrigation amounts**

304 The maize yield ranged from -35% to +15%, and in most cases decreased by up to 20%. The decrease
305 in yield was due mainly to an increase in the N stress index during the vegetative phase of maize (Figure
306 4a). As expected, due to automatic irrigation, maize experienced little or no water stress during the
307 vegetative and reproductive phases whatever the fallow period management (Table 3 & Figure 4ab).
308 However, most simulations did not result in an increase in irrigation volume, which agrees with the
309 small influence of cover crops on SWC. The few cases in which irrigation volume increased (to 30 mm)
310 occurred after terminating ryegrass and the bispecific mixture on April 15. This phenomenon occurred
311 at dry sites in the few years that had a severe drought in spring. Water and N stress occurred mainly
312 after ryegrass or the bispecific mixture, while yield increased mainly after vetch. The correlation
313 between a decrease in yield and increase in N stress was high with R² equal to 0.88 and 0.83 for the
314 vegetative and reproductive phase, respectively, while no correlation was predicted between decreased
315 yield and water stress.

316 (Insert Figure 4 around here)

317 **3.4.3. Rainfed sunflower yield**

318 The change in sunflower yield ranged from -40 to +20%, with a mean decrease of 10% for all types of
319 cover crop species and management practices (Figure 5). During the vegetative phase, N stress increased
320 slightly but water stress increased greatly in spring with April termination of ryegrass and the bispecific
321 mixture in dry years, especially in 1996, 2010 and 2016. For dry sites (AUZ, LEC and PEY), termination
322 on March 15 with low spring rainfall decreased yield. During the reproductive phase, most large
323 decreases in yield were due to N stress after ryegrass or the bispecific mixture with termination date at
324 March 15 or April 15. Sunflower yield increased mainly after vetch and, to a lesser extent, the bispecific
325 mixture, as for maize. Correlations between the decrease in yield and increase in N stress were

326 significant, with R^2 equal 0.52 and 0.51 for the vegetative and reproductive phase, respectively. Like for
327 maize, and despite the absence of irrigation, there was little or no correlation between a decrease in yield
328 and changes in water stress due to cover crops ($R^2 \approx 0.00$ and 0.27 in the vegetative and reproductive
329 phase, respectively).

330 (Insert Figure 5 around here)

331 **4. Discussion**

332 **4.1. Cover crops decreased nitrate leaching and drainage as a function of their** 333 **sowing date**

334 The simulations indicate that cover crops decreased nitrate leaching effectively during the fallow period
335 compared to bare soil and were less effective with legume than with non-legume species, as experiments
336 and other simulation studies have shown (Constantin et al., 2010; Tonitto et al., 2006; Tribouillois et al.,
337 2015a). As cover crop biomass and N uptake depend greatly on sowing and termination dates along with
338 climate conditions, the sowing date is crucial for optimal growth in autumn and to decrease nitrate
339 leaching effectively (Constantin et al., 2015a). For instance, late sowing does not allow for optimal
340 growth of cover crops due to low temperatures and solar radiation, which are reinforced by a dry autumn
341 (Bodner et al., 2010). Sowing date also has a strong influence on decreasing water drainage. The earlier
342 the cover crop is sown, the larger the decrease in water drainage, as shown in a previous study in this
343 region (e.g. Meyer et al., 2020).

344 Termination date also influenced the production of cover crop biomass, which also depended on the
345 species. In a dry autumn, late sowing of vetch can limit its growth strongly. Species with rapid growth
346 in summer and a short crop cycle, such as white mustard, stop growing in late autumn/early winter,
347 when they reach senescence (Bodner et al., 2007). Conversely, species such as ryegrass have a strong
348 ability to resume growth in spring, and their biomass can double or triple in a few weeks in spring. White
349 mustard, with relatively low biomass, increased evapotranspiration less than vetch or ryegrass, which
350 grew for a longer period. The spring regrowth of ryegrass and the bispecific mixture increased
351 evapotranspiration strongly. This kind of growth had the greatest influence on the water balance in the

352 present study, with the largest decrease in drainage when the cover crop was terminated in April.
353 Although drainage varied greatly among sites (by a mean of 100 to more than 600 mm), the decrease
354 due to cover crops varied little among them. Unlike the decrease in nitrate leaching, which was similar
355 to that under bare soil, the decrease in drainage could represent a small or large percentage of total
356 drainage. Consequently, the influence of cover crops on drainage could be limited through management
357 choices at sites with low annual drainage. Management practices should be adapted in certain cases to
358 decrease biomass production in order to decrease cover crop evapotranspiration and the decrease in
359 drainage (Nielsen et al., 2015; Tribouillois et al., 2018).

360 **4.2. Cover crops decreased total SWC but did not influence seedbed SWC**

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

374 **4.3. Cover crops induced mainly N stress, sometimes decreasing cash crop yield**

375 Cover crops have a well-documented influence on succeeding crop yields. Increased maize yields have
376 been reported, particularly with legume cover crops such as vetch (Clark et al., 1997). We also predicted
377 increased maize and sunflower yields after vetch in the present study. This increase is due to the

378 additional supply of mineral N after decomposition of legume residues, which are richer in N due to
379 symbiotic N₂ fixation and the green manure effect of these legumes (Tosti et al., 2014; Tribouillois et
380 al., 2015b). Conversely, sowing a non-legume cover crop during the fallow period can result in mineral
381 N pre-emption, which is detrimental to the growth of the succeeding cash crop when doses of N fertiliser
382 are not increased (Alvarez et al., 2017). In the present study, decreases in SNC were predicted as a
383 function of the termination date and cover crop species. A late termination date could induce a larger
384 decrease in SNC. We predicted a decrease in maize and sunflower yields under certain conditions, which
385 was explained mainly by N stress but also by water stress in specific cases. Maize experienced water
386 stress in spring 2011 during the vegetative phase, despite automatic irrigation, which did not increase
387 due to cover crops. Severe drought and high temperatures in April and May 2011 explained this high
388 stress, which strongly decreased yield. Except for a few cases, the succeeding cash crop suffered mainly
389 from N stress and pre-emptive competition from cover crops, resulting in a decrease in yield (by 0.5-3.0
390 Mg.ha⁻¹), especially for late spring termination. Marcillo and Miguez (2017) reported the importance of
391 adapting the cover crop termination date to avoid a decrease in yield due to lower SNC. We also
392 predicted the largest decrease in yield with the latest termination date (the day before sowing the cash
393 crop), due to a phase of net N organisation after incorporating cover crop residues. This influence was
394 greater for cover crops with strong growth in spring, resulting in lower SNC. For sunflower, grown
395 under dry conditions, we also predicted a decrease in yield due to water and N stress. However, as
396 mentioned, sowing vetch, regardless of its termination date, or mustard, which stops growing in winter,
397 or autumn termination of ryegrass, can avoid the decrease in yield of the succeeding cash crop.

398 Sowing a legume cover crop increases the yield of the succeeding cash crop as it avoids N stress due to
399 pre-emptive competition (Tonitto et al., 2006). However, legume cover crops increased the risk of nitrate
400 leaching compared to that with non-legumes, as they take up less N from the soil due to symbiotic N₂
401 fixation (Thorup-Kristensen and Nielsen, 1998). Nevertheless, sowing legumes remains more effective
402 than bare soil and could be beneficial, especially for sites with low nitrate leaching, to promote the green
403 manure effect and thus use less N fertiliser. Combining legumes and non-legumes could be an interesting
404 compromise as this type of mixture has performed well for the management of mineral N, to

405 significantly decrease leaching and increase the green manure effect (Tosti et al., 2014, 2012;
406 Tribouillois et al., 2015a). Cover crop mixtures that include legumes and non-legumes, along with
407 adapted management (i.e. species, sowing and termination dates), could be an effective solution to
408 provide several ecosystem services depending on the specific objectives and a site's soil and climate,
409 especially to avoid water problems (White et al., 2017). In zones prone to nitrate leaching, farmers
410 should sow more legume/non-legume mixtures and limit the use of pure legumes during fallow periods.
411 In dry regions, late termination of grass cover crops, such as ryegrass, is strongly discouraged to avoid
412 the risk of mineral N and water pre-emptions which decrease the yield of the succeeding cash crop
413 (Alonso-Ayuso et al., 2014).

414 **4.4. Study boundaries and extrapolation in space and time**

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

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

432 succeeding cash crop could increase. In a deeper soil, the stress could decrease, as roots can grow more
433 deeply and access more water and abiotic resources.

434 The present study highlighted the influence of termination date on evapotranspiration, water drainage
435 and soil water and mineral N availability for the succeeding cash crop, confirming the results obtained
436 by Alonso-Ayuso et al. (2018). Residue management after termination also modified the influence of
437 cover crops on the soil water balance. Stopping growth and leaving cover crop residues on the soil
438 surface limits the increase in evapotranspiration caused by the decrease in soil evaporation compared to
439 mouldboard ploughing (Gabriel et al., 2019). This difference in evapotranspiration can increase surface
440 SWC, as several studies show for the upper 0.2 m of soil (Moschler et al., 1967; Stipešević and Kladičko,
441 2005).

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

450 In climate change context, cover crops are an interesting tool to overcome some crucial issues by
451 reducing efficiently nitrate leaching avoiding indirect N₂O emissions in aquifers. Some studies have
452 shown that this efficiency remains in climate change context as well (Alonso-Ayuso et al., 2018;
453 Tribouillois et al., 2018). Cover crops also increase C storage in soil and enhance the green gashouse
454 emissions balance over the long term, contributing to mitigate climate change effect (Launay et al.,
455 2021; Tribouillois et al., 2018). However two main possible drawbacks should be point out, particularly
456 in dry region with climate change: the reduction of drainage could increase with higher biomass
457 production of cover crops and pre-emptive competition for water and N for the following crop could
458 worsen, as suggested by Alonso-Ayuso et al. (2018). According to these authors and our results,

459 adapting the termination date of the cover crops with earlier termination should allow to avoid or limit
460 these effects and still reduce N and GHG pollution.

461 **5. Conclusion**

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

479

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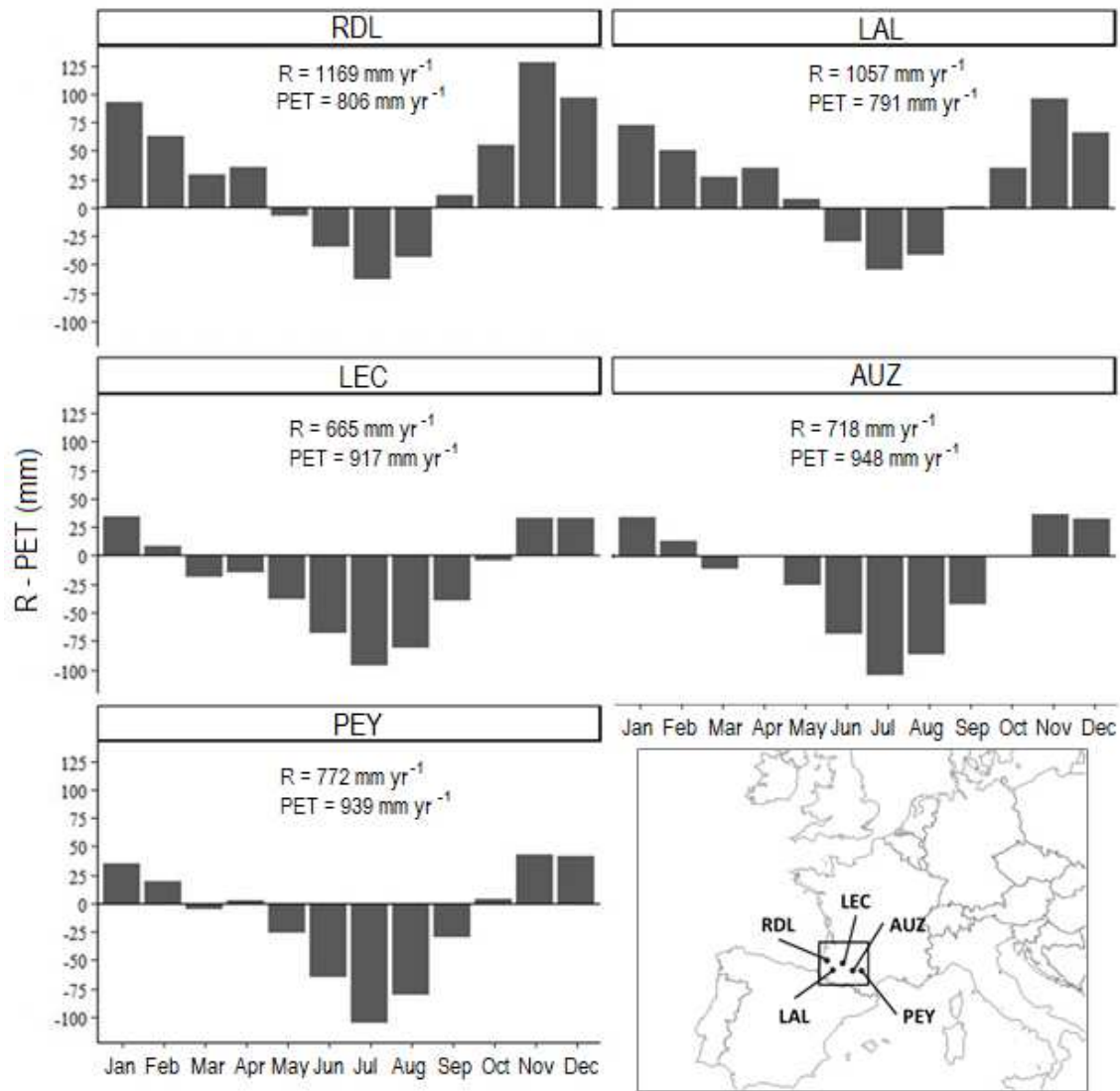
645 **Conflict of interest**

646 The authors declare that they have no conflict of interest.

647 **Acknowledgments**

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

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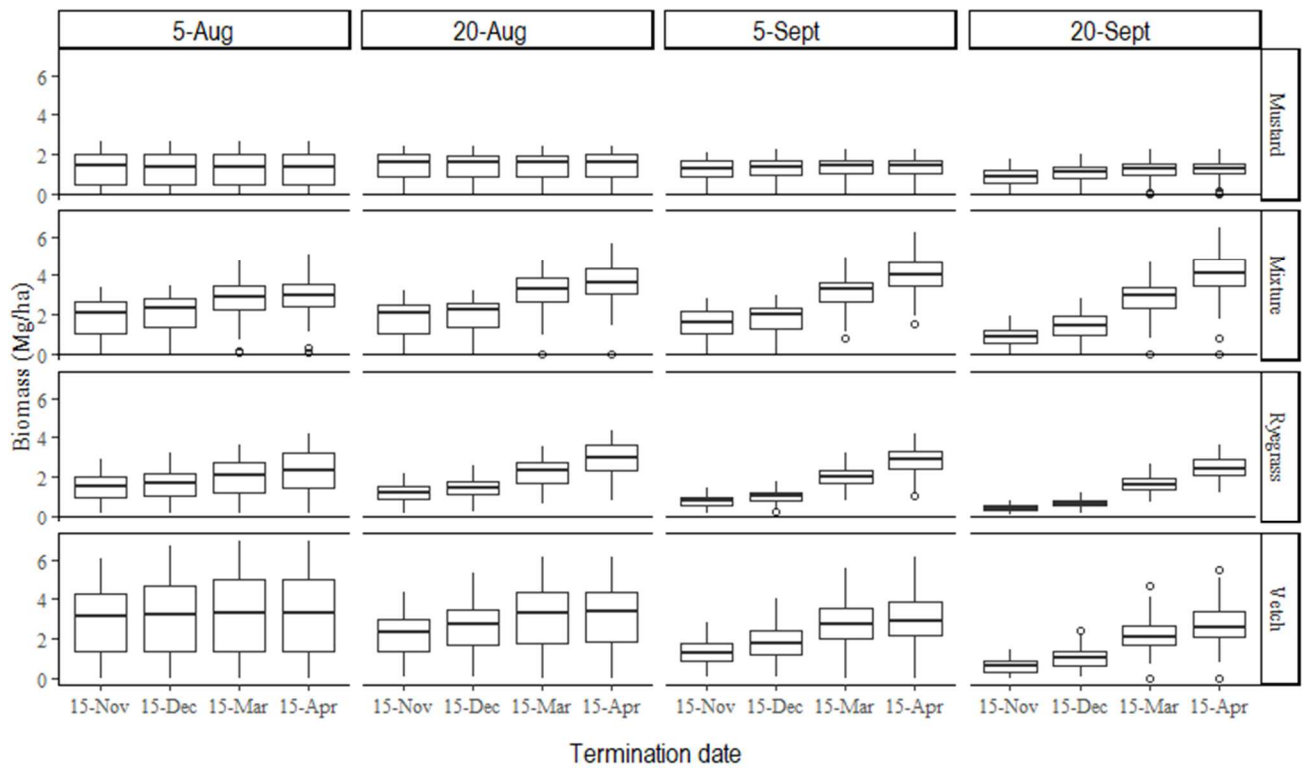


Figure 2. Boxplots of final cover crop biomass by the three main factors explaining its variance: species, termination and sowing date, all sites gather.

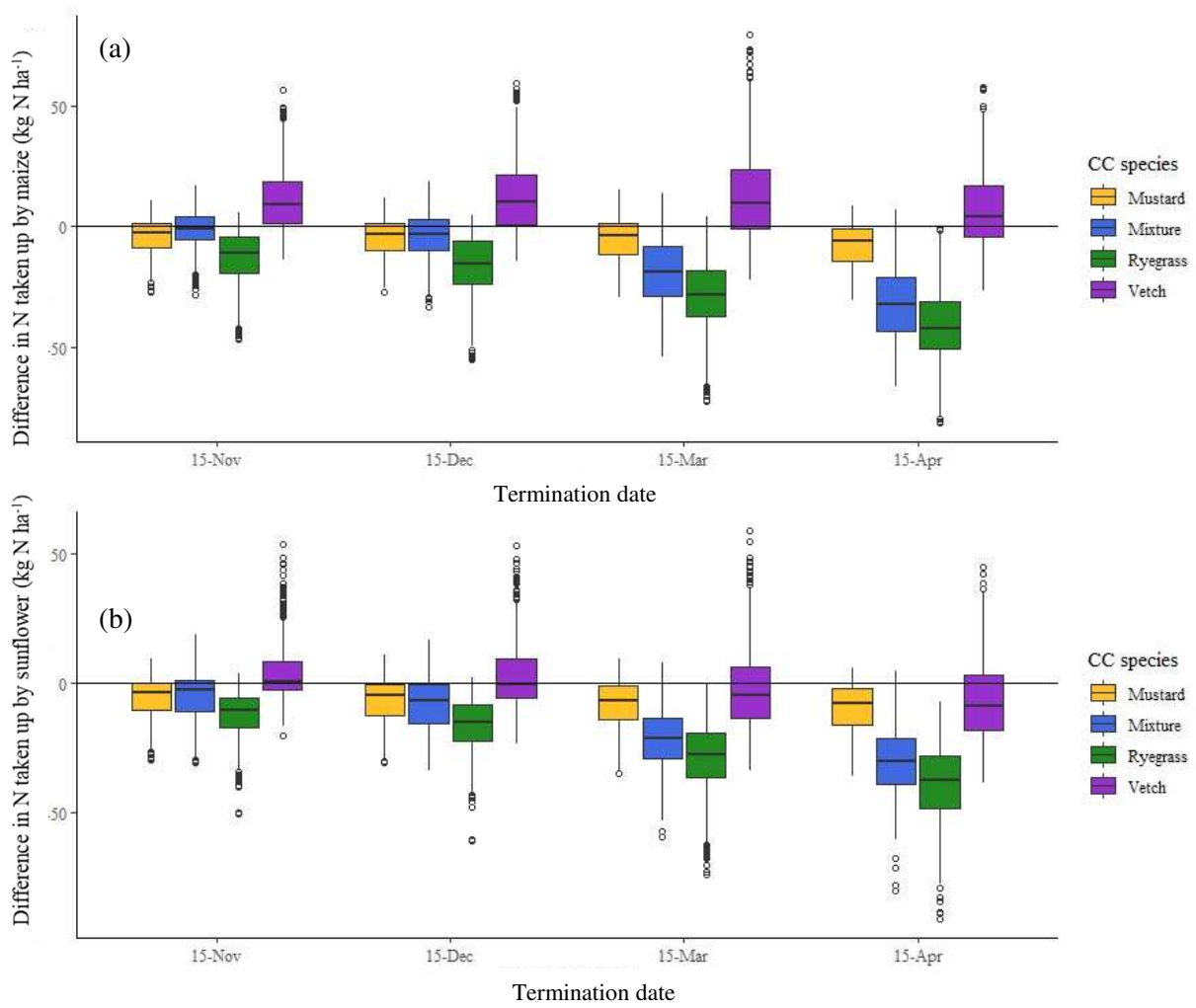


Figure 3. Difference in (a) maize and (b) sunflower nitrogen (N) uptake as a function of the previous cover crop (CC) compared to that with bare soil. Mixture represents a mixture of Ethiopian mustard and red clover. Error bars indicate 1.5 times the interquartile range. Values above 0 means that the 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.

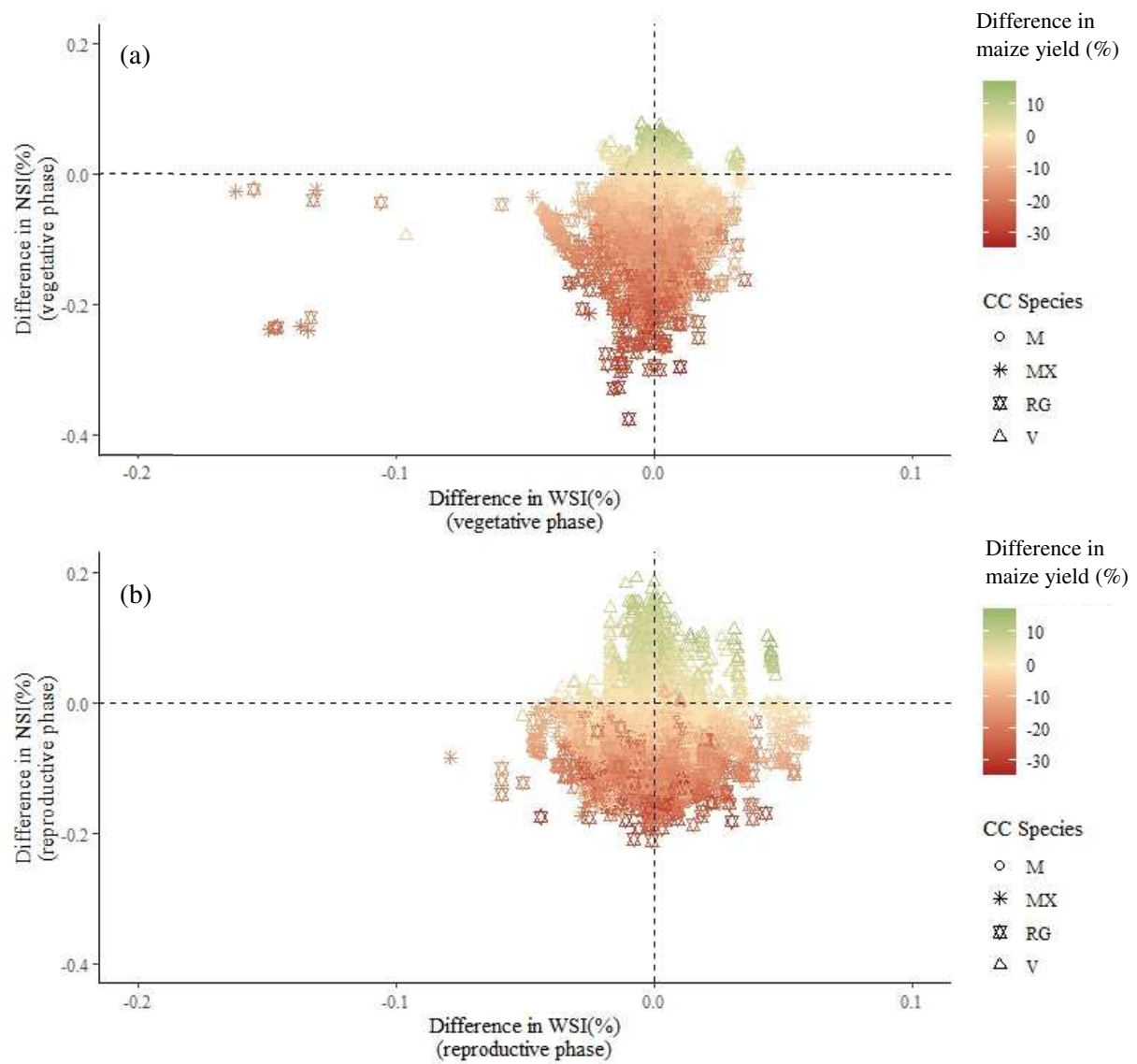


Figure 4. Difference in the water stress index (WSI) and nitrogen stress index (NSI) due to a cover crop in (a) vegetative and (b) reproductive phases of the following irrigated maize and the influence on yield (in colour) compared to a bare soil fallow period. Cover crop (CC) species were white mustard (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.

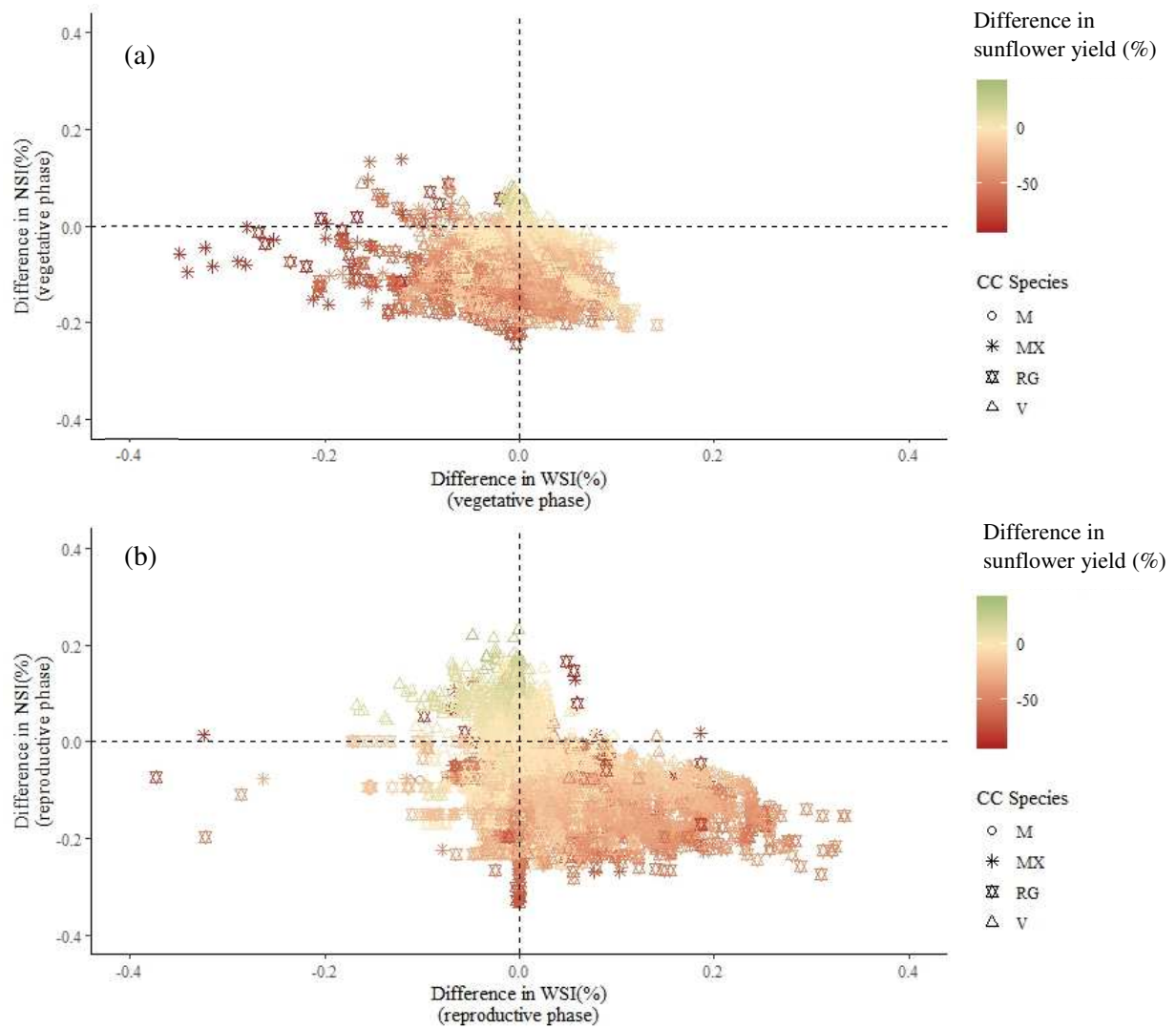


Figure 5. Difference in the water stress index (WSI) and nitrogen stress index (NSI) due to a cover crop in (a) vegetative and (b) reproductive phases of the following rainfed sunflower and the influence on yield (in colour) compared to a bare soil fallow period. Cover crop (CC) species were white mustard (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	<ul style="list-style-type: none"> • No cover crop • Italian ryegrass • White mustard • Common vetch • Mixture of red clover and Ethiopian mustard
Soil tillage date and depth	<ul style="list-style-type: none"> • Date of cover crop sowing to a depth of 3 cm • April 15 to a depth of 10 cm
Cover crop sowing date	<ul style="list-style-type: none"> • August 5 • August 20 • September 5 • September 20
Cover crop termination date	<ul style="list-style-type: none"> • November 15 • December 15 • March 15 • April 15
Cover crop residue management	<ul style="list-style-type: none"> • Mulch left on the soil surface • Ploughed
Cash crop sowing date	April 16
Cash crop harvest date	<ul style="list-style-type: none"> • Maize: November 20 • Sunflower: October 16
Cash crop irrigation	<ul style="list-style-type: none"> • Maize: irrigated at 85% of requirements • Sunflower: rainfed
Cash crop nitrogen supply	<ul style="list-style-type: none"> • 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
<u>Fallow period, from August 1st to April 15th</u>															
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
<u>Crop succession: bare soil + maize</u>															
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
<u>Crop succession: bare soil + sunflower</u>															
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
<u>April 15th, at the cash crop sowing date</u>															
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
<u>Next cash crop: maize</u>															
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 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 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 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 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
<u>Next cash crop: sunflower</u>															
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 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 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 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 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

1 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 ($F \times F$). Termination = termination date,
 2 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
<u>Difference compared to bare soil during the fallow period</u>												
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
<u>Difference compared to bare soil on April 15</u>												
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

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