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1 **Numerical exploration of the impact of hydrological connectivity on rainfed annual crops in**  
2 **Mediterranean hilly landscapes**

3

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17 Within hilly agricultural landscapes, topography induces lateral transfers of runoff water,  
18 so-called interplot hydrological connectivity. Runoff water from upstream plots can infiltrate  
19 downstream plots, thus influencing the water content in the root zone that drives crop  
20 functioning. The current study aims to comprehensively investigate the impact of runoff on  
21 crop functioning in the context of Mediterranean rainfed annual crops. To quantify this  
22 impact, we conduct a numerical experiment using the AquaCrop model and consider two  
23 hydrologically connected plots. The experiment explores a range of upstream and  
24 downstream agro-pedo-climatic conditions: crop type, soil texture and depth, climate forcing,  
25 and the area of the upstream plot. The experiment relies on data collected over the last 25  
26 years in OMERE, an environment research observatory in northeastern Tunisia, and data  
27 from literature. The results show that the downstream infiltration of upstream runoff has a  
28 positive impact on crop functioning in a moderate number of situations, ranging from 16%  
29 (wheat) to 33% (faba bean) as the average across above ground biomass and yield. Positive  
30 impact is mostly found for higher soil available water capacity and under semiarid and dry  
31 subhumid climate conditions, with a significant impact of rainfall intra-annual distribution in  
32 relation to crop phenology. These results need to be deepened by considering both a wider  
33 range of crops and future climate conditions.

34 **Abstract**

35 Within hilly agricultural landscapes, topography induces lateral transfers of runoff water, so-called  
36 interplot hydrological connectivity. Runoff water from upstream plots can infiltrate downstream plots,  
37 thus influencing the water content in the root zone that drives crop functioning. The impact of runoff  
38 on crop functioning can be crucial for optimizing agricultural landscape management strategies.  
39 However, to our knowledge, no study has specifically focused on the impact on crop yield. The  
40 current study aims to comprehensively investigate the impact of runoff on crop functioning in the  
41 context of Mediterranean rainfed annual crops. To quantify this impact, we conduct a numerical  
42 experiment using the AquaCrop model and consider two hydrologically connected plots. The  
43 experiment explores a range of upstream and downstream agro-pedo-climatic conditions: crop type,  
44 soil texture and depth, climate forcing, and the area of the upstream plot. The experiment relies on  
45 data collected over the last 25 years in OMERE, an environment research observatory in northeastern  
46 Tunisia, and data from literature. A key finding in the results is that water supply through  
47 hydrological connectivity can enhance annual crop production, under semiarid and subhumid climate  
48 conditions. Specifically, the results show that the downstream infiltration of upstream runoff has a  
49 positive impact on crop functioning in a moderate number of situations, ranging from 16% (wheat) to  
50 33% (faba bean) as the average across above ground biomass and yield. Positive impact is mostly  
51 found for higher soil available water capacity and under semiarid and dry subhumid climate  
52 conditions, with a significant impact of rainfall intra-annual distribution in relation to crop phenology.  
53 These research needs to be expanded by considering both a wider range of crops and future climate  
54 conditions.

55 **Keyword**

56 Hydrological connectivity; Runoff-runon process; Water infiltration; Rainfed agriculture; Annual  
57 crops; Crop production; Mediterranean

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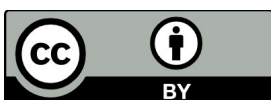


## 60 1. Introduction

61 Water resources are limited within the Mediterranean basin, with <1,000 m<sup>3</sup>/capita/yr in the eastern  
62 and southern Mediterranean (Fader et al. 2020). These resources are unevenly distributed in time and  
63 space, partly due to contrasting rainfall patterns (Blinda and Thivet 2009; Daccache et al. 2016; Fader  
64 et al. 2020). This water context is set to worsen because of (1) water resource over-exploitation to  
65 meet the growing food demand (Karabulut et al. 2018; Souissi et al. 2019) and (2) climate change  
66 consequences such as rainfall decreases, up to 30% (Lange et al. 2020), an increase of evaporative  
67 demand (Fader et al. 2020) and a concentrations of intra-annual rainfall distributions (Ramos and  
68 Martínez-Casasnovas 2006). As the largest water user, the agricultural sector has long been under  
69 threat, with subsequent challenges for food security (Yang and Zehnder 2002). Rainfed annual crops  
70 are significantly affected by water issues because (1) they fully depend upon rainfall as a water  
71 resource, and (2) their shallow root systems make them vulnerable to water shortages (Hossain et al.  
72 2020).

73 Mediterranean policies for water resources management have mainly oriented to support irrigated  
74 agriculture (Besbes et al. 2014; Nouri et al. 2020). As a result, less attention has been given to rainfed  
75 agriculture, which uses less water per unit area (Anderson et al. 2016). Nevertheless, it would be  
76 possible to further improve rainfed agricultural productivity by implementing strategies that  
77 (1) reduce crop water needs, with species suited to drought conditions, or (2) increase water  
78 availability in the root zone by favoring runoff/rainwater infiltration or minimizing evaporative losses.  
79 The amount of water that infiltrates the root zone can be increased using water harvesting techniques  
80 (e.g., planting pits, terraces) at different spatial scales, from plot to landscape (Yadari et al. 2019;  
81 Tadros et al. 2021; Molénat et al. 2023). These techniques are suitable for landscapes with hilly  
82 topography that allows for the spatial redistribution of surface runoff (Ammar et al. 2016; Mekki et al.  
83 2018). The benefits of these techniques in reducing runoff, promoting infiltration, increasing the soil  
84 water content, and enhancing crop yield have been demonstrated, particularly in Sub-Saharan Africa  
85 (see Wolka et al. (2018) for a review). Most of the studies conducted in the Mediterranean basin have  
86 demonstrated the benefits of the techniques in terms of reducing runoff or increasing the soil water  
87 content (Schiettecatte et al., 2005). To our knowledge, no study has specifically focused on the impact  
88 on crop yield.

89 Hydrological connectivity refers to water transfer across different areas of the landscape (Bracken  
90 and Croke, 2007). In Mediterranean hilly landscapes, surface runoff predominantly drives interplot  
91 hydrological connectivity, redistributing rainfall between plots. This runoff-runon process occurs  
92 when runoff from upstream plots infiltrates downslope cultivated plots with greater infiltration  
93 capacity (Jones et al., 2013; Van Loo and Verstraeten, 2021), thus enhancing water availability in the  
94 root zone (Fig. 1)(Howes and Abrahams, 2003). While the impact of interplot hydrological



95 connectivity on hydrological processes like stream flow generation is well recognized (Nanda et al.,  
96 2019; Zuecco et al., 2019; Saco et al., 2020), few studies evaluate its effect on crop functioning.  
97 Typically, crop functioning is studied using multilocal methods that assume hydrological  
98 independence among plots, overlooking the influence of hydrological connectivity (Van Gaelen et al.,  
99 2017). However, understanding this impact is crucial for optimizing agricultural landscape  
100 management strategies, particularly in arid to semiarid Mediterranean regions where water scarcity is  
101 a primary limiting factor for crop growth (Daccache et al., 2016; Araya et al., 2017) and where lateral  
102 water transfer primarily occurs through surface runoff (Mekki et al., 2006).

103 Studying the impact of interplot hydrological connectivity on rainfed annual crops in hilly  
104 Mediterranean regions requires careful consideration of key environmental factors affecting both  
105 downstream crop functioning and upstream runoff generation. Considering these factors enables the  
106 exploration of their potential influence on hydrological connectivity. Various elements can influence  
107 surface runoff, including rainfall patterns (Chen et al. 2016), hydrodynamic properties, soil moisture  
108 (Schoener and Stone 2019), agricultural practices (Prosdocimi et al. 2016), vegetation cover type  
109 (Nunes et al. 2011; Liu and Lobb 2021), and the impluvium area, representing the upstream  
110 contributing area for runoff input (Gnouma 2006). Furthermore, the functioning of downstream crops  
111 can be affected by the infiltration of upstream runoff and other environmental factors, such as climate  
112 (comprising rainfall and evapotranspiration demand), soil properties (such as the organic matter  
113 content and available water capacity), and agricultural practices (including fertilization and soil  
114 management) (Mbava et al. 2020). Investigating the potential influences of these environmental  
115 factors on hydrological connectivity can be pursued through field campaigns or numerical  
116 experiments using modeling. The latter approach is more suitable, as it allows for (1) the  
117 consideration of a wide range of environmental factors and (2) the disentanglement of the combined  
118 effects of environmental factors with hydrological connectivity.

119 The objective of this article is to study the impact of water infiltration due to the runoff-runon  
120 process on crop functioning. We focus on rainfed annual crops in a Mediterranean hilly landscape,  
121 emphasizing two main agronomic variables: above ground biomass and yield. In Section 2, we  
122 introduce the numerical experiment by describing the chosen modeling approach, the various  
123 influential factors to consider, and the strategy for analyzing the results. Section 3 presents and  
124 discusses the analysis of modeling simulations: we first examine the occurrence of situations with a  
125 significant impact on hydrological connectivity and then assess the importance of environmental  
126 conditions (climate, upstream runoff, soil texture and depth) on this impact. Finally, we discuss the  
127 prospects of this study, considering that it represents a preliminary step toward an integrated  
128 catchment-scale approach.

129

[Fig. 1 about here.]



130

## 131 2. Materials and methods

### 132 2.1. General framework

133 The numerical experiment is based on simulating crop functioning in a downstream plot receiving  
134 surface runoff from an upstream plot that is hydrologically connected, and by considering crops, soils  
135 and climate typical of Mediterranean conditions (Fig. 2). The downstream plot is supplied with water  
136 from both rainfall and runoff simulated in the upstream plot. Assumptions include homogeneity in  
137 parameters, state variables, and fluxes within each plot, as well as complete transfer of upstream  
138 runoff to the downstream plot due to hydrological connectivity. Here, we provide an overview of the  
139 numerical experiment setting, and a detailed presentation is provided in Supplementary materials -  
140 Section 1.

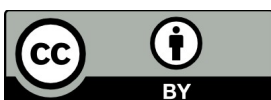
141 The numerical experiment is conducted using the AquaCrop model (Raes et al. ,2009; Steduto et  
142 al., 2009), chosen for its performances to simulate crop functioning as well as surface runoff in water-  
143 driven conditions typical of arid to semiarid Mediterranean regions. Furthermore, AquaCrop has been  
144 extensively validated for a range of state variables related to water budgets and crop growth across  
145 various Mediterranean conditions (Garcia-Lopez et al, 2014, Toumi et al., 2016), especially under the  
146 conditions considered in the current study (Dhouib et al., 2022).

147 [Fig. 2 about here.]

148 The simulations of downstream crop functioning with additional water supply from upstream  
149 runoff, span a wide range of typical Mediterranean conditions. This includes a diversity of  
150 environmental drivers that influence crop functioning, such as (1) varying crop types with distinct  
151 hydrological functioning and phenology , (2) different soil available water capacity in relation to  
152 varying soil depth and texture via hydrodynamic properties (Cousin et al. 2022), and (3) inter- and  
153 intra-annual variability of climate forcing over decades, including rainfall, temperature and reference  
154 evapotranspiration.

155 In the downstream plot, we consider a range of upstream runoff magnitudes to account for the  
156 Mediterranean hydrological variability. The upstream runoff is simulated based on environmental  
157 factors like crop type, soil available water capacity, and climate forcing. An additional factor is the  
158 drained area of the upstream plot , hereafter referred to as the impluvium, characterized using the ratio  
159 of upstream to downstream plot areas. A low ratio indicates a downstream plot near a hillslope  
160 summit in a landscape, while a high ratio signifies a downstream plot along or at the bottom of a  
161 hillslope.

162 To simulate typical Mediterranean conditions, we use the OMERE observatory database



163 ([www.obs-omere.org](http://www.obs-omere.org), Molénat et al. 2018), that meets specific requirements. It encompasses a range  
164 of climate forcings that spans the last three decades and observations collected within the Kamech  
165 catchment (Cap Bon Peninsula, northeastern Tunisia) that is representative of semiarid Mediterranean  
166 regions in terms of crops, soil, and climate.

## 167 2.2. Overview of the AquaCrop crop model

168 Detailed presentations of AquaCrop (<https://www.fao.org/aquacrop/en/>) are provided by Raes et al.  
169 (2009) and Steduto et al. (2009). Here, we outline the specificities related to our methodological  
170 choices.

171 AquaCrop is a crop model designed to simulate crop functioning and the principal components of  
172 the water balance. Specifically, tailored for arid and semiarid environments, it is categorized as a  
173 water-driven model (Todorovic et al. 2009). Indeed, it adjusts crop growth based on vegetation  
174 transpiration, itself driven by root zone soil moisture. This characteristic makes it well suited for  
175 Mediterranean regions, where water acts as the principal limiting factor for agricultural production.

176 AquaCrop simulates, on a daily time step, the components of soil water balance across the soil–  
177 plant-atmosphere continuum (infiltration and runoff, deep percolation and capillary rise, soil  
178 evaporation and vegetation transpiration), as well as plant growth and production (canopy crop cover,  
179 root growth, above ground biomass, yield). Crop transpiration ( $Tr$ ) is derived from canopy crop cover  
180 ( $CC$ ) and reference evapotranspiration ( $ET_0$ ). Above ground biomass ( $AGB$ ) is then derived from  $Tr$   
181 and normalized water productivity ( $WP^*$ ), which accounts for atmospheric  $CO_2$  concentration. Yield  
182 ( $Yld$ ) is calculated as the product of  $AGB$  and the harvest index ( $HI$ ). Runoff is determined using the  
183 empirical curve number method that accounts for crop type, agricultural practice, and hydrological  
184 soil group in relation to the soil infiltration rate and antecedent soil moisture. The soil water balance is  
185 calculated by discretizing the soil into five horizons based on pedological characteristics.

186 The AquaCrop forcing variables encompass climate data (e.g., air temperature, reference  
187 evapotranspiration  $ET_0$ , rainfall, and atmospheric  $CO_2$  concentration) on a daily timescale. The model  
188 parameters consist of soil properties (texture and depth, soil moisture at field capacity, permanent  
189 wilting point and saturation, saturated hydraulic conductivity), cultural parameters (e.g., maximum  
190 canopy cover, crop coefficient), and agricultural practice data (e.g. fertilization, sowing date).

## 191 2.3. Setting the agro-pedo-climatic conditions

192 We assumed the same variability for the agro-pedological conditions within the upstream and  
193 downstream plots. All possible scenarios for each of the two plots are next combined to ensure the  
194 representativeness of the resulting AquaCrop simulations. When dealing with climate conditions,  
195 including rainfall, air temperature and  $ET_0$ , for instance, we assumed uniformity across the two plots.



### 196 2.3.1. Crop types and subsequent crop parameters

197 We chose wheat as the cereal crop and faba bean as the legume crop for two main reasons. First, they  
198 are among the main rainfed crops in the Kamech catchment (Mekki et al. 2006) and the broader  
199 Mediterranean region (Jourdan, 2022). Second, wheat and faba bean differ significantly in  
200 phenological cycle duration, agricultural practices (sowing and harvest dates) and in hydrological  
201 functioning (different soil cover rates implying different infiltration-runoff ratios). Faba bean, a row  
202 crop with a short phenological cycle, contrast with wheat, a cover crop with a longer phenological  
203 cycle. Crop parameters for wheat and faba bean used in the model are detailed in the Table 1.  
204 Supplementary materials - Sections 2 details the setting, according to the study area, of the choice of  
205 sowing dates and the fertilization rates.

206 [\[Table 1 about here.\]](#)

### 207 2.3.2. Soil characteristics and hydrodynamic properties

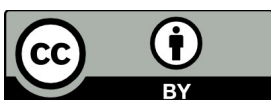
208 Soil hydrodynamic properties include (1) soil moisture at field capacity (FC), at permanent wilting  
209 point (PWP), and at saturation (Sat), as well as (2) the saturated hydraulic conductivity (Ksat). These  
210 properties are determined based on soil textures estimated from 10 soil pits collected at various  
211 locations within Kamech catchment according to the USDA classification (Coulouma et al. 2017).  
212 Then, the soil textures are converted into hydrodynamic properties using the nominal values proposed  
213 by the AquaCrop user guide (Table 2). Three different depths, namely, 0.5 m, 1 m, and 1.5 m are  
214 chosen on the basis of the variability of soil depth observed in Kamech catchment (Molénat et al.  
215 2018). By combining three soil textures and three soil depths, we simulate nine situations for soil  
216 available water capacity.

217 [\[Table 2 about here.\]](#)

### 218 2.3.3. Climate forcing

219 A 25-year climate period from September 1, 1995, to August 31, 2019 is chosen, corresponding to the  
220 maximum window for which the OMERE data are available. The climate forcing data are air  
221 temperature, rainfall, reference evapotranspiration  $ET_0$ .

222 For this climate series, the annual averages for rainfall, air temperature during the vegetation  
223 growing season (October to May) and  $ET_0$  are 629 mm, 14.8°C and 1310 mm, respectively  
224 (Supplementary Materials - Section 3, Fig. SF2). The years 1996 and 2019 are the wettest, with  
225 cumulative rainfall of 1036 mm and 862 mm, respectively. The years 1997, 2002 and 2016 are the  
226 driest, with cumulative rainfall of 406 mm, 394 mm and 416 mm, respectively. Regarding air  
227 temperature, 1999 and 2009 are the coldest years, with an average air temperature of 14.2°C over the  
228 crop growth period [October - May]. The years 2001, 2002 and 2007 are the warmest, with an average





229 air temperature of 15.4°C over the crop growth period [October - May] (Supplementary Materials -  
230 Section 3, Fig. SF2).

231 To deepen the analysis of AquaCrop simulations, we classify the years of the climate series using  
232 the FAO aridity index (Spinoni et al. 2014). This index expresses aridity as the ratio of atmospheric  
233 water supply (rainfall) to atmospheric water demand ( $ET_0$ ). We opt for this index because (1) it  
234 considers several climate variables when using  $ET_0$  to quantify aridity, and (2) it is suitable for  
235 analyzing AquaCrop simulations since AquaCrop involves  $ET_0$  when calculating the above ground  
236 biomass. According to the FAO aridity index, the climate series comprises two subhumid years (SH),  
237 10 dry subhumid years (DSH), and 13 semiarid years (SA), accounting for occurrences of 8%, 40%,  
238 and 52%, respectively (Fig. 3). Additional details about the calculation of the FAO aridity index are  
239 provided in the Supplementary Materials - Section 3.

240 [Fig. 3 about here.]

#### 241 **2.4. Simulating the upstream runoff**

242 The upstream runoff is quantified using AquaCrop simulations based on the agro-pedo-climatic  
243 conditions discussed in Section 2.3. The agro-pedo-climatic conditions include two crop types, nine  
244 situations for soil available water capacity (three soil textures and three soil depths), and 25 years of  
245 climate. To account for the impluvium area, simulated upstream runoff is weighted by the  $\alpha$  ratio, that  
246 is, the ratio of the upstream to the downstream plot area (Fig. 2), which is set to three nominal values:  
247 0.5, 1 and 2. By combining two crop types, nine conditions for soil available water capacity, and three  
248 ratios of the upstream to the downstream plot area, we obtain 54 situations of upstream runoff and  
249 thus 54 simulated time series of runoff, each spanning 25 years. Subsequently, each simulated time  
250 series of upstream runoff is added to the corresponding time series of rainfall in the downstream plot.

251 The set of simulated time series of upstream runoff, after weighting by the  $\alpha$  ratio, depicts a range  
252 of annual cumulative values from 9 mm to 691 mm, representing 2% to 97% of the annual rainfall,  
253 depending on the year. To further analyze the impact of upstream runoff on downstream crop  
254 functioning, we classify these annual cumulative values into four classes relative to three quartiles  
255 (Table 3). We refer hereafter to classes of upstream runoff.

256 [Table 3 about here.]

#### 257 **2.5. Simulating downstream crop functioning**

258 Downstream crop functioning is simulated with AquaCrop, considering the agro-pedo-climatic  
259 conditions (Section 2.3) and the upstream runoff (Section 2.4). For each of the two downstream crops  
260 (wheat and faba bean) and each of the nine downstream situations in terms of soil available water  
261 capacity, 54 AquaCrop simulations are run, varying in the simulated input of upstream runoff. This



262 results in 486 simulations for each of the two downstream crops to be linked for comparison purposes  
263 to the corresponding nine reference simulations (3 soil depths, 3 soil textures) of crop functioning  
264 without upstream runoff from connectivity. On a yearly basis, these 486 simulations amount to 12,150  
265 simulations for each downstream crop, totaling 24,300 for both.

## 266 2.6. Simulation analysis

267 To study the impact of water infiltration due to the runoff-runon process on downstream crop  
268 functioning, we focus on two agronomic variables driven by crop functioning, namely, above ground  
269 biomass (AGB) and yield (Yld). We conduct a quantitative analysis, which involves calculating the  
270 relative differences in AGB and Yld between simulations with and without connectivity (Equation 1,  
271  $X_{wc}$  and  $X_{oc}$  stand for the value of the simulated variable with and without connectivity,  
272 respectively). This allows us to (1) globally quantify, for all considered situations, the impact of  
273 upstream runoff by hydrological connectivity on the functioning of the downstream crops (wheat and  
274 faba bean) and (2) understand the influence, on this impact, of environmental conditions within the  
275 downstream plot (upstream runoff, climate forcing, soil texture and depth, crop).

$$276 \quad \Delta (AGB \text{ or } Yld) = \frac{X_{wc} - X_{oc}}{X_{oc}} \quad (\text{Equation 1})$$

277

278 For each of the two downstream crops, the relative difference  $\Delta$  is calculated at the annual timescale  
279 along the 25-year time series for any of the 486 combinations (3 soil depths, 3 soil textures, 54  
280 upstream runoff). A year Y is considered a hydrological year spanning from the beginning of  
281 September of the calendar year [Y-1] to the end of August of the calendar year [Y]. This results in a  
282 total of 12,150 relative differences calculated for AGB and Yld for each crop in the downstream plot  
283 and for each of the 25 years.  $\Delta > 0$  ( $< 0$ ) indicates that additional water input through hydrological  
284 connectivity has a positive (negative) impact, since it leads to an increase (a decrease) in AGB and  
285 Yld compared to the case without connectivity.

286 Before analyzing all relative differences  $\Delta$ , it is necessary to define criteria for selecting only  
287 realistic and accurate simulations used in the analysis :

288 ● The first criteria relies on the crop yield. For this, we filter AquaCrop simulations based on an  
289 agro-economic constraint, namely, yield. Following field-based expert recommendations, we  
290 select simulations with Yld (wheat)  $> 0.5$  ton/ha and Yld (faba bean)  $> 0.25$  ton/ha, knowing that  
291 yields below these values are considered null from an agro-economic constraint. To avoid  
292 eliminating significant impact changes between with and without connectivity, this filter is applied  
293 to simulations with connectivity if  $\Delta > 0$  and without connectivity if  $\Delta < 0$ .

294 ● A second criteria defines a threshold value for a significant change ( $\Delta$ ) to account for uncertainties  
295 in the AquaCrop simulations. For this, we refer to Dhouib et al. (2022), who reported that the



296 model satisfactorily simulates AGB, with a relative error between observations and simulations of  
297 approximately 11%. Therefore, we choose a threshold of 0.11 for the absolute value for  $\Delta$ , above  
298 which the impact of water input through connectivity is considered significant as it exceeds the  
299 modeling uncertainty. If negative (positive)  $\Delta$  values are greater (lower) than or equal to -0.11  
300 (0.11), we consider that the impact of water input through hydrological connectivity on crop  
301 functioning is insignificant. Since the model has not been evaluated for yield in the study area, we  
302 use the same threshold on  $\Delta$  for AGB and Yld.

303

### 304 3. Results and discussion

#### 305 3.1. Above ground biomass (AGB) and yield (Yld)

306 The analysis of relative differences between simulations with and without connectivity indicates that  
307 in most situations (combinations of soil available water capacity derived from soil texture and depth,  
308 upstream runoff, and climate year), the contribution of hydrological connectivity through runoff  
309 infiltration has a nonsignificant impact on AGB/Yld. This holds true for both downstream crops of  
310 wheat and faba bean, with more than 85%/77% and 67%/62% of the calculated differences falling  
311 between -0.11 and 0.11, respectively (Fig. 4, Fig. SF3 and SF4 un Supplementary Materials – Section  
312 4).

313

[Fig. 4 about here.]

314 Beyond the overall results, there are situations in which the contribution of hydrological  
315 connectivity through runoff infiltration significantly increases AGB and Yld for both wheat and faba  
316 bean crops. The increase is more pronounced for faba bean than for wheat, with 33% of the relative  
317 differences (average over AGB and Yld values) being greater than 0.11 for faba bean, compared to  
318 16% only for wheat. This suggests that faba bean is more sensitive to water shortages than wheat and  
319 that additional water input via the infiltration of upstream runoff contributes to alleviating this  
320 shortage. This is confirmed by the analysis of the water stress coefficient  $K_s$ . Indeed, in 69% of the  
321 situations considered, faba bean is more often stressed than wheat since it has a lower  $K_s$  (Fig. SF5 in  
322 Supplementary Materials - Section 5), while the increase in  $K_s$  induced by upstream runoff averages  
323 9% for faba bean and only 2% for wheat (data not shown). This greater sensitivity of faba bean to  
324 water shortage can be explained by (1) a shorter phenological cycle, making its functioning more  
325 sensitive to intra-annual variations in rainfall, and (2) a shorter root system (Hamblin and Tennant  
326 1987) that does not allow the crop to use water stored in deeper soil layers. These simulation results  
327 converge with the observations of Daryanto et al. (2017), who reported a drought-based yield  
328 reduction more important for legume crops than for cereal crops.

329 When a positive impact is observed, the increase induced by water input through hydrological

330 connectivity is higher for grain yield (Yld) than for above ground biomass (AGB). This is ascribed to  
331 the way that AquaCrop calculates Yld as the product of AGB and the harvest index (HI), where HI is  
332 sensitive to water stress (Ali and Talukder 2008; AquaCrop user manual). Thus, the latter has a  
333 double effect on Yld via both AGB and HI.

334 We also observe another type of situation, much rarer (only 3% of relative differences), where  
335 water input through hydrological connectivity leads to negative relative differences (Fig. 4). This  
336 indicates a decrease in both above ground biomass (AGB) and yield (Yld), which may be attributed to  
337 waterlogging (Liu et al. 2020). Since the frequency of such a situation is low, we mainly focus on  
338 situations with a positive impact of hydrological connectivity for the remainder of this paper.

### 339 3.2. Influence of environmental conditions

340 We investigate the influence of environmental conditions of the downstream plot (hydrological  
341 conditions, soil texture and depth, and climate) to understand how some of these conditions can lead  
342 to positive impacts. For each downstream crop, we categorize the set of significant  $\Delta$  values  
343 ( $\Delta > 0.11$ ) for both above ground biomass (AGB) and yield (Yld) based on the respective classes of a  
344 given environmental factor (i.e., four classes for upstream runoff, three classes for texture, three  
345 classes for soil depth and three classes for climate years). Thus, the cumulative distribution across all  
346 classes for any environmental factor and any  $\Delta$  type (AGB, Yld) adds up to 100%. The resulting  
347 statistics are presented in Tables 4, ST3, ST4 and ST6 and are utilized in the subsequent three  
348 subsections.

349 [\[Table 4 about here.\]](#)

#### 350 3.2.1. Hydrological conditions

351 We emphasize three significant results related to the simulated water dynamics, from runoff to the soil  
352 water content, in connection with AGB and Yld variations.

353 First, in situations with insignificant impact ( $\Delta \in [-0.11 ; +0.11]$ ), the occurrences of the  $\Delta$  values are  
354 evenly distributed across the four classes of upstream runoff (Supplementary materials - Section 6,  
355 Table ST3). In situations with positive impact, the occurrences of the  $\Delta$  values are lower for the first  
356 two classes of upstream runoff that correspond to the lowest cumulative values (R1 and R2 classes in  
357 Table 3), as they account for 40% to 46% of cases depending on the crop and the production variable  
358 (AGB or Yld). Conversely, the occurrence of the  $\Delta$  values is larger for the last two classes (R3 and  
359 R4) that correspond to the highest cumulative values, with 54% to 60% of cases.

360 Second, in situations with a positive impact, the increase in the water infiltration amount induced by  
361 upstream runoff averages 10% and 7% relative to wheat and faba bean, respectively (Table ST4).  
362 Meanwhile, the increase in infiltration for situations with an insignificant impact is only 8% and 6%  
363 for the two crops.



364 Third, situations with a positive impact show an average increase in the simulated root zone water  
365 content (wRZ) over the crop cycle of 41% and 24% for wheat and faba bean, respectively (Table  
366 ST4). In contrast, for situations with an insignificant impact, the simulated root zone water content  
367 increases by only 2% and 1% for these crops.

368 From these three main results, we can infer first and clearly that the hydrological connectivity in  
369 Mediterranean regions can have an impact on crop growth. Nevertheless, these results suggest that the  
370 increase in AGB and Yld depends only partially on the amount of upstream runoff. While positive  
371 impact situations are predominantly associated with a significant increase in upstream runoff, even  
372 small increases in upstream runoff (Class R1 in Tables 3 and ST3) and in the resulting infiltration  
373 (Table ST3) can also lead to positive impacts. For our case study, the impact of hydrological  
374 connectivity through the runoff-runon process on crop production seems to be primarily determined  
375 by the increase in the root zone water content during the crop cycle. Our study suggests thus that the  
376 impact of hydrological connectivity is not solely determined by the total annual water amount brought  
377 by runoff and subsequent infiltration to downslope plot. Rather it is more influenced by the  
378 relationship between runoff (and subsequent infiltration) and the increase of soil water in the root  
379 zone during the crop cycle. The remaining results of our study provide insights in this relationship.

380

### 381 3.2.2. Soil texture and depth

382 For both crops (wheat and faba bean) and both agronomic variables (above ground biomass AGB and  
383 yield Yld), the deeper the soil, the larger the occurrence of significant  $\Delta$  values (Table 4). Indeed, the  
384 occurrence intervals are [12% - 15%], [31% - 42%], and [43% - 57%] for 0.5, 1, and 1.5 m deep soil,  
385 respectively. When dealing with soil texture, a large occurrence of significant  $\Delta$  values is observed for  
386 clay-loam (CL) soils, with an average value of 47% when merging the two crops and two agronomic  
387 variables (Table 4). Compared to CL soils, lower occurrences are observed for C and SCL, with  
388 average values (over the two crops and two agronomic variables) of 30% and 24%, respectively  
389 (Table 4).

390 These results are consistent with the concept of soil available water capacity and align with recent  
391 literature on this topic. We observed increases in above ground biomass (AGB) and yield (Yld)  
392 following the infiltration of upstream runoff, mainly for clay-loam (CL) soils and deeper soils. This  
393 observation is explained by (1) a larger soil available water capacity for CL and deeper soils, allowing  
394 for a greater storage of water in the root zone (Alkassem et al. 2022; Cousin et al. 2022) and (2) a soil  
395 conducive to root zone development in terms of depth (van Leeuwen 2022).

396 To illustrate these statements, we use the example of wheat sown in 2002 in clay-loam soil and  
397 compare crop functioning across the three soil depths considered (Fig. 5). For the same temporal  
398 pattern and amount of water received from upstream runoff through hydrological connectivity ( $\alpha$  ratio



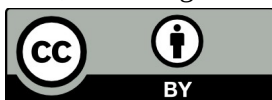
399 is 2 in the simulations of Fig. 5), the above ground biomass increases from 1.5 ton/ha at a soil depth  
400 of 0.5 m to 6.1 ton/ha at a soil depth of 1.5 m. This difference can be explained by changes in the root  
401 zone water content in relation to soil depth. Indeed, upstream runoff increases the amount of water  
402 that infiltrates into the soil by 8% for the three soils between simulations with and without  
403 connectivity (data not shown). This further increases wRZ by 2%, 35% and 88% for the 0.5 m, 1 m  
404 and 1.5 m soil depths, respectively, between simulations with and without connectivity (data not  
405 shown). These changes in the root zone water content can be related to changes in crop functioning  
406 throughout the crop growth cycle, as discussed below.

- 407 ● The comparison of crop functioning variables for different soil depths, including water storage in  
408 the root zone, transpiration, canopy cover, and above ground biomass, suggests that from the  
409 beginning of the crop cycle to January 10, the wheat crop exhibits a similar rooting depth for the  
410 three soil depths, thus accessing the same amount of water in the soil.
- 411 ● From January 10 onwards, the crop roots continue to expand downward in the 1 m and 1.5 m deep  
412 soils, while they reach their maximum growth in the shallow soil (0.5 m depth). Consequently, the  
413 root zone water content decreases for the crop in the shallow soil (0.5 m depth), whereas it  
414 increases for the crop in the deeper soils (1 m and 1.5 m depth). This leads, for the shallow soil, to  
415 reductions in canopy cover (CC), crop transpiration (Tr), and above ground biomass (AGB)  
416 50 days later (March 1) when the root zone water content reaches a critical level. Conversely, these  
417 reductions are not observed for the crop in the 1 m and 1.5 m deep soils that still benefit from  
418 sufficient water content within the root zone.
- 419 ● For wheat sown in 1 m and 1.5 m deep soils, the initial deviation between the two temporal courses  
420 of the root zone water content occurs on March 2. Specifically, the root zone water content slightly  
421 increases for the 1.5 m deep soil due to deepening root growth, whereas it decreases for the 1 m  
422 deep soil as the root system has reached its maximum depth. This leads, for the 1 m depth soil, to  
423 reductions in CC, Tr, and AGB 50 days later (April 15), when the soil water content reaches a  
424 critical level. Conversely, these reductions are not observed until senescence of the crop in the  
425 1.5 m deep soils that still benefit from sufficient water content within the root zone.

426 [Fig. 5 about here.]

### 427 3.2.3. Climate forcing

428 When the influence of climate conditions is analyzed, the increases in above ground biomass (AGB)  
429 and yield (Yld) due to water input through hydrological connectivity are primarily noticeable in dry  
430 subhumid (DSH) and semiarid (SA) years, while being almost negligible in subhumid (SH) years  
431 (Table 4). Indeed, occurrence intervals for significant  $\Delta$  values ( $\Delta > 0.11$ ) are [0% - 5%],  
432 [40% - 49%], and [46 - 60%] for the SH, DSH, and SA years, respectively. For wheat, 0% of  
433 significant  $\Delta$  values are observed in SH years, 42% in DSH years, and 58% in SA years. For faba  
434 bean, 4% of significant  $\Delta$  values are observed in SH years, and the remainder are evenly distributed



435 between DSH and SA years (approximately 48%). Notably, these results may be biased by the  
436 uneven distribution of climate years, comprising 8% of SH years, 40% of DSH years, and 52% SA  
437 years. This uneven distribution is an inherent limitation of the study that relies on field observations  
438 of climate forcing, although the distribution of significant  $\Delta$  values does not completely align on that  
439 of climate years.

#### 440 **3.2.3.1. During semi-arid years**

441 During SA years, the downstream infiltration of upstream runoff, even in small quantities,  
442 increases the water content in the root zone, thereby increasing AGB and Yld. On average, during  
443 these years, the increase in the soil water content in the root zone due to upstream runoff is 29% for  
444 wheat and 18% for faba bean (Supplementary materials - Section 6, Table ST5). The example of the  
445 year 2016 is characteristic of the increase in the root zone water content induced by infiltration. This  
446 year is classified as an SA year according to the FAO aridity index (Fig. 3), with annual rainfall  
447 accumulation largely below the 25-year average (Supplementary materials - Section 3, Fig. SF2).  
448 During this year, the downstream plot benefits from additional runoff between a lower value of 9 mm  
449 and an upper value of 105 mm (data not shown), depending on the environmental conditions of the  
450 upstream plot (soil, crop, and impluvium area). For the two limits mentioned above, infiltration in the  
451 downstream plot (cultivated with wheat) increases by 1% and 18%, respectively, wRZ increases by  
452 4% and 29%, AGB increases by 27% and 112%, and Yld increases by 35% and 406% (median values  
453 of all downstream soils, data not shown).

#### 454 **3.2.3.2. During dry subhumid years**

455 The influence of climate forcing on the increase in above ground biomass (AGB) and yield (Yld)  
456 may be linked to the intra-annual variability in rainfall, especially in dry subhumid years. Indeed,  
457 when analyzing the occurrences of positive impact, calculated for faba bean in dry subhumid years  
458 considering all downstream soil textures and depths and all runoff amounts (Supplementary  
459 Materials - Section 7, Fig. SF6), we note the following trends.

- 460 ● On the one hand, water input through hydrological connectivity has a frequent positive impact on  
461 AGB and Yld (occurrence > 10% in Fig. SF6) for a group of years, namely, 1998, 1999, 2004,  
462 2010, and 2013. These years are characterized by annual rainfall accumulations of 750 mm,  
463 700 mm, 708 mm, 650 mm, and 622 mm, respectively (Supplementary materials - Section 3,  
464 Fig. SF2).
- 465 ● On the other hand, water input through connectivity has a less frequent positive impact on AGB  
466 and Yld (occurrence < 10% in Fig. SF6) for 2003, 2005, and 2009, characterized by very similar  
467 annual rainfall accumulations: 728 mm, 651 mm, and 793 mm, respectively Supplementary  
468 materials - Section 3, Fig. SF2).

469 Therefore, the infiltration of runoff water from upstream is more likely to increase the above ground





470 biomass (AGB) and yield (Yld) of the faba bean crop for the first group of years, but this is less likely  
471 for the second group. To gain further insight into this observation, we examine simulations without  
472 hydrological connectivity considering a clay-loam soil with a 1 m depth for two dry subhumid years:  
473 in 2003 (728 mm of rainfall), the occurrence of positive impacts among all tested situations is rather  
474 low (8%), whereas it is much greater (61%) in 2004 (708 mm of rainfall) (Supplementary Materials -  
475 Section 7, Fig. SF6). In the situation without hydrological connectivity, AGB and Yld are lower in  
476 2004 than in 2003. Therefore, the potential crop production increase by upstream runoff is higher for  
477 2004 than for 2003. The analysis of monthly rainfall (Fig. 6a) reveals differences in the intra-annual  
478 distribution of rainfall between the two years, leading to subsequent variations in crop growth.

479 ● During the hydrological year 2004, September, December, and March are characterized by high  
480 monthly rainfall, thereby increasing the amount of water that infiltrates into the soil (Fig. 6c). In  
481 contrast, the hydrological year 2003 has a drier start compared to 2004 (except for November).  
482 From January onwards, the rainfall in 2003 is more substantial than that in 2004. This intra-annual  
483 distribution of rainfall results in a higher water content in the root zone between September and  
484 February in 2004 than in 2003 (Fig. 6d). However, this difference in the soil water content  
485 between the two years does not have a particularly positive impact on the growth of faba bean in  
486 2004, as the crop is in the early stages of its cycle (Fig. 6e).

487 ● From February onwards, the water content in the root zone in 2003 is higher than that in 2004 due  
488 to greater rainfall in January, February, and April. This explains the better vegetation development  
489 in 2003.

490 [\[Fig. 6 about here.\]](#)

491 To compare the impact of hydrological connectivity on crop production during these two years (2003  
492 and 2004), we consider the same agro-pedological situation considered above (faba bean cultivated in  
493 a clay-loam soil with 1 m depth) for a downstream plot receiving typical upstream runoff (from an  
494 upstream plot cultivated with faba bean in a 1 m deep clayey soil). Then, water input from  
495 hydrological connectivity increases infiltration and wRZ by 8% and 10%, respectively, in 2004 and  
496 by 11% and 6% in 2003, respectively. Furthermore, the resulting increase in yield is far larger in 2004  
497 (73%) than in 2003 (13%), which is ascribed to the intra-annual variability in rainfall discussed above.

498

#### 499 **4. Conclusion**

500 We report the first complete numerical experiment aimed at quantifying the impact of hydrological  
501 connectivity between plots on Mediterranean rainfed crop production.

502 The results show that water input through hydrological connectivity has a positive impact on  
503 agricultural production depending on environmental conditions related to crops, climate forcing, and





504 soil properties. Climate forcing significantly influences the impact of hydrological connectivity from  
505 both yearly rainfall and the intra-annual distribution of rainfall. A positive impact is observed in dry  
506 subhumid and semiarid climate years, suggesting that this impact may become more pronounced in  
507 light of the forecasted climate change.

508

509 These novel results pave the way of optimizing agricultural landscape management strategies.  
510 Future investigation should expand environmental conditions and address the current study's  
511 assumptions. It should include detailed spatial and temporal variability in agricultural plots,  
512 considering how upstream runoff and agricultural practices modify soil properties. The cumulative  
513 impact of runoff across successive plots and the role of subsurface water flow, particularly in hilly  
514 Mediterranean regions, also need investigation. Lastly, coupling crop models with distributed  
515 hydrological models could enhance the relevance of runoff simulations within cultivated landscapes.

516

517



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## 532 **Conflicts of interest/Competing interests**

533 The authors have no conflicts of interest to declare that are relevant to the content of this article.

## 534 **Ethics approval**

535 Not applicable.

## 536 **Consent to participate**

537 Not applicable

## 538 **Consent for publication**

539 Not applicable

## 540 **Availability of data and material**

541 The datasets generated during and/or analysed during the current study are available from the  
542 corresponding author on reasonable request.

## 543 **Code availability**

544 Code will be made available on request

545

## 546 **Authors' contributions**



547 Conceptualization, F.J., I.M., J.M., L.P. and R.Z-C.; Methodology, F.J., J.M., L.P. and M.D.;  
548 Software, M.D.; Validation, F.J., I.M., J.M., L.P., M.D. and R.Z-C.; Formal analysis, J.M., L.P. and  
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553



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708 **List of figures**

709

710 **Fig.1 :**A typical Mediterranean hilly landscape showing hydrological connectivity (arrows) between  
711 agricultural upstream and downstream plots (surrounded by a solid line) as well as the hydrographic  
712 network (long dashed line). The landscape is located in Tunisia -Kamech catchment (© photo J.  
713 Molénat).

714 **Fig. 2:** Representative diagram of the numerical experiment setting. It includes the spatial layout of  
715 the two upstream (Up) and downstream (Do) plots, connected by runoff water from the upstream (R).  
716 The table lists the factors considered for each plot, and the ranges of attributes/values are discussed  
717 hereafter. Every crop ('crop X' or 'crop Y') corresponds to either to faba bean or wheat, the setup of  
718 which is given in Section 2.3.1.

719 **Fig. 3:** Classification of climate years according to the FAO aridity index . Each year Y is a  
720 hydrological year that spans from the beginning of September of calendar year [Y-1] to the end of  
721 August of the year [Y].

722 **Fig. 4:** Occurrences of insignificant, positive, and negative relative differences calculated for wheat  
723 (a) and for faba bean (b). The fully colored bars and the white bars outlined in color correspond to the  
724 above ground biomass and the yield, respectively.

725 **Fig. 5:** Comparison of the temporal evolution of the (a) runoff (R) and precipitation (P), (b)  
726 infiltration (Infl), (c) root zone water content (wRZ), (d) canopy cover (CC), (e) transpiration (Tr),  
727 and (f) above ground biomass (AGB) among three different soil depths for wheat sown in 2002 in  
728 clay-loam soil, with the same amount of infiltrated upstream runoff. CL-0.5 m, CL-1 m, and CL-1.5  
729 m correspond to clay-loam soil depths of 0.5 m, 1 m, and 1.5 m, respectively. In all of these  
730 simulations, the  $\alpha$  ratio is 2, indicating that the upslope runoff (R) in (a), used as a water input, is  
731 multiplied by 2.

732 **Fig. 6:** (a), (b) and (c) are monthly cumulative rainfall (Cum P), simulated runoff (Cum R) and  
733 simulated infiltration (Cum Infi), respectively, in 2003 (blue bars) and 2004 (grey bars). (d) and (e)  
734 are simulated water content in the root zone (wRZ) and simulated canopy cover (CC), respectively,  
735 without connectivity in 2003 (blue line) and 2004 (grey line) for faba bean sown in a clay-loam soil  
736 with a 1 m depth.

737



738 **List of tables**

739

740 **Table 1:** Crop parameters values used for AquaCrop simulations. Conservative (i.e., independent of  
741 species, practices, and climate) and non-conservative (i.e., dependent on species, practices, and  
742 climate) are presented (Alaya et al., 2019).

743

744 **Table 2:** Soil parameters values used for AquaCrop simulations. C, CL, and SCL correspond to clay,  
745 clay-loam, and sandy-clay-loam textures, respectively. PWP, FC and Sat correspond to soil moisture  
746 at the permanent wilting point, at field capacity and at saturation, respectively. Ksat corresponds to  
747 saturated hydraulic conductivity.

748

749 **Table 3:** Classification of the cumulative values of upstream runoff. R1, R2, R3, and R4 correspond  
750 to Classes 1, 2, 3, and 4, respectively, of cumulative values of upstream runoff. Q1, Q2, and Q3  
751 correspond to the 1st quartile, median, and 3rd quartile, respectively.

752

753 **Table 4:** Percentage occurrence of significant and positive relative differences ( $\Delta > 0.11$ ) categorized  
754 by environmental factors. The abbreviations SH, DSH, and SA represent subhumid, dry subhumid,  
755 and semiarid years, respectively. The labels R1, R2, R3, and R4 correspond to upstream runoff classes  
756 1, 2, 3, and 4, respectively. The labels C, CL, and SCL stand for clay, clay-loam, and sandy-clay-loam  
757 textures, respectively. AGB and Yld are the above ground biomass and the yield, respectively.

**Table 1:** Crop parameters values used for AquaCrop simulations. Conservative (i.e., independent of species, practices, and climate) and non-conservative (i.e., dependent on species, practices, and climate) are presented (Alaya et al., 2019).

<b>CROP PARAMETERS</b>	<b>Wheat</b>	<b>Faba bean</b>
<b>Conservative parameters</b>		
Base temperature (°C)	0	5.5
Cutoff temperature (°C)	26	30
Canopy cover per seedling at 90% emergence (CC <sub>0</sub> ) (cm <sup>2</sup> )	1.5	5
Canopy growth coefficient (CGC) (in fraction CC per GDD)	0.0052	0.0105
Maximum canopy cover (CC <sub>x</sub> ) in fraction soil cover	0.99	0.8
Crop coefficient for transpiration at CC = 100%	1.1	1.1
Decline in crop coefficient after reaching CC <sub>x</sub> (%/day)	0.15	0.15
Canopy decline coefficient (CDC) (in fraction per GDD)	0.004	0.008
Water productivity normalised for ET <sub>0</sub> and CO <sub>2</sub> (WP*) (g/m <sup>2</sup> )	13.4	13
Leaf growth threshold (Pupper)	0.2	0.25
Leaf growth threshold (Pflower)	0.65	0.6
Leaf growth stress coefficient curve shape	5	3
Stomatal conductance threshold (Pupper)	0.65	0.6
Stomata stress coefficient curve shape	2.5	3
Senescence stress coefficient (Pupper)	0.7	0.75
Senescence stress coefficient curve shape	2.5	3
<b>Non conservative parameters</b>		
GDD from sowing to emergence	140	122
GDD from sowing to maximum rooting depth	1670	741
GDD from sowing to start senescence	1861	1286
GDD from sowing to maturity (length of crop cycle)	2777	1411
GDD from sowing to flowering	1543	879
Length of the flowering stage (GDD)	189	128
GDD building up of harvest index during yield formation	980	495
Reference harvest index (HI <sub>0</sub> ) (%)	45	30

**Table 2:** Soil parameters values used for AquaCrop simulations. C, CL, and SCL correspond to clay, clay-loam, and sandy-clay-loam textures, respectively. PWP, FC and Sat correspond to soil moisture at the permanent wilting point, at field capacity and at saturation, respectively. Ksat corresponds to saturated hydraulic conductivity.

<b>SOIL PARAMETERS</b>				
<b>Hydrodynamic properties</b>	<b>Unit</b>	<b>Texture</b>		
		C	CL	SCL
PWP	m <sup>3</sup> /m <sup>3</sup>	0.39	0.23	0.20
FC	m <sup>3</sup> /m <sup>3</sup>	0.54	0.39	0.32
Sat	m <sup>3</sup> /m <sup>3</sup>	0.55	0.50	0.47
Ksat	mm/j	35	125	225

**Table 3:** Classification of the cumulative values of upstream runoff. R1, R2, R3, and R4 correspond to Classes 1, 2, 3, and 4, respectively, of cumulative values of upstream runoff. Q1, Q2, and Q3 correspond to the 1st quartile, median, and 3rd quartile, respectively.

<b>Runoff class</b>	<b>Quartiles for the annual cumulative values of runoff</b>
Class 1 (R1)	Cumulative annual runoff < 51 mm (Q1)
Class 2 (R2)	51 mm (Q1) ≤ Cumulative annual runoff < 95 mm (Q2)
Class 3 (R3)	95 mm (Q2) ≤ Cumulative annual runoff < 170 mm (Q3)
Class 4 (R4)	Cumulative annual runoff ≥ 170 mm (Q3)

**Table 4:** Percentage occurrence of significant and positive relative differences ( $\Delta > 0.11$ ) categorised by environmental factors. The abbreviations SH, DSH, and SA represent subhumid, dry subhumid, and semiarid years, respectively. The labels R1, R2, R3, and R4 correspond to upstream runoff classes 1, 2, 3, and 4, respectively. The labels C, CL, and SCL stand for clay, clay-loam, and sandy-clay-loam textures, respectively.

AGB and Yld are the above ground biomass and the yield, respectively.

Crop	Variable	Climate			Upstream runoff				Texture			Soil depth		
		SH	DSH	SA	R1	R2	R3	R4	C	CL	SCL	0.5m	1.0m	1.5m
Wheat	AGB	0	44	56	22	24	27	27	33	45	22	12	31	57
	Yld	0	40	60	16	25	30	29	31	47	22	20	32	48
Faba bean	AGB	5	49	46	17	23	30	30	25	50	25	15	42	43
	Yld	4	45	51	18	24	28	30	29	45	26	15	42	43

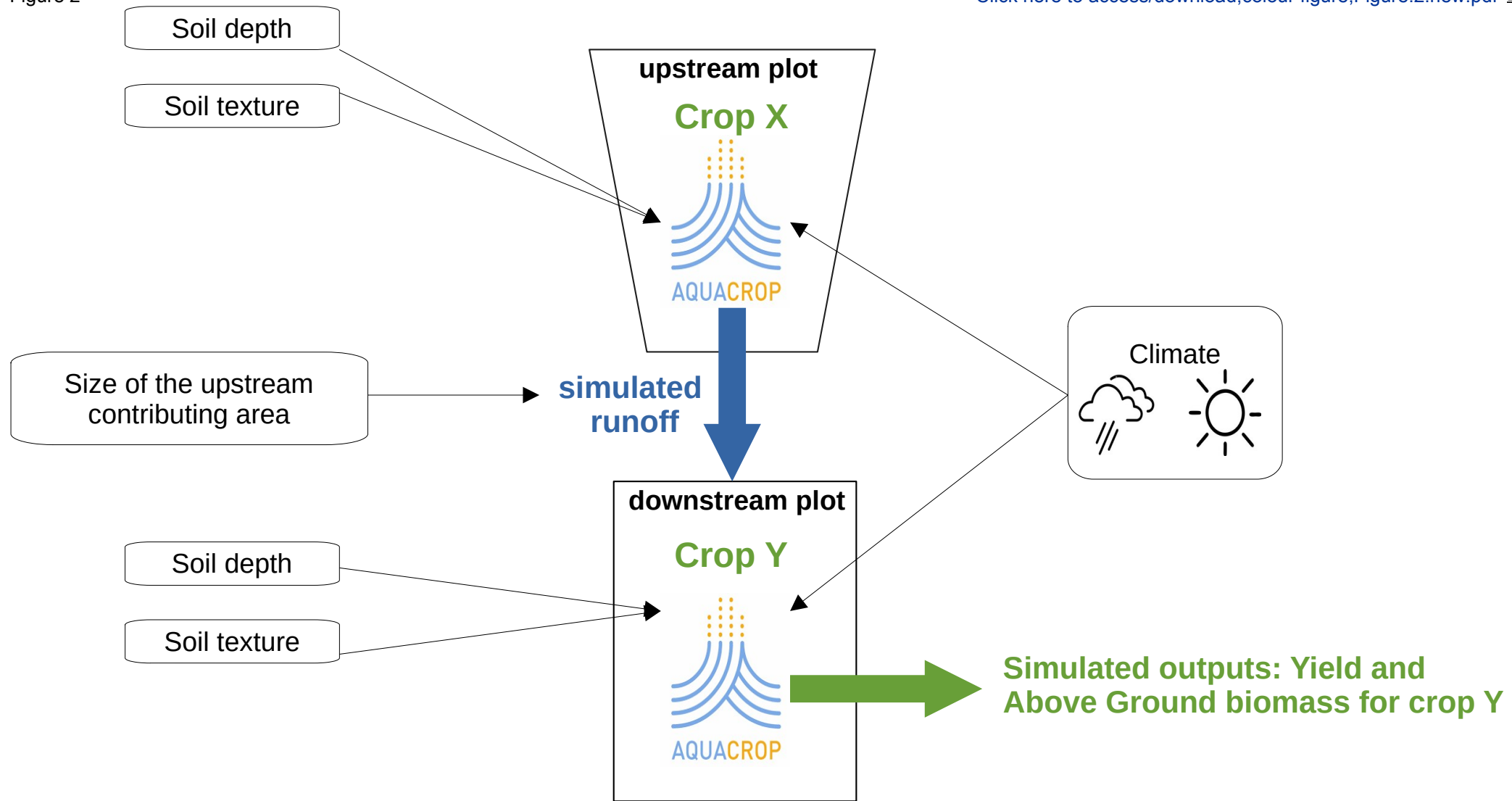


Figure 1

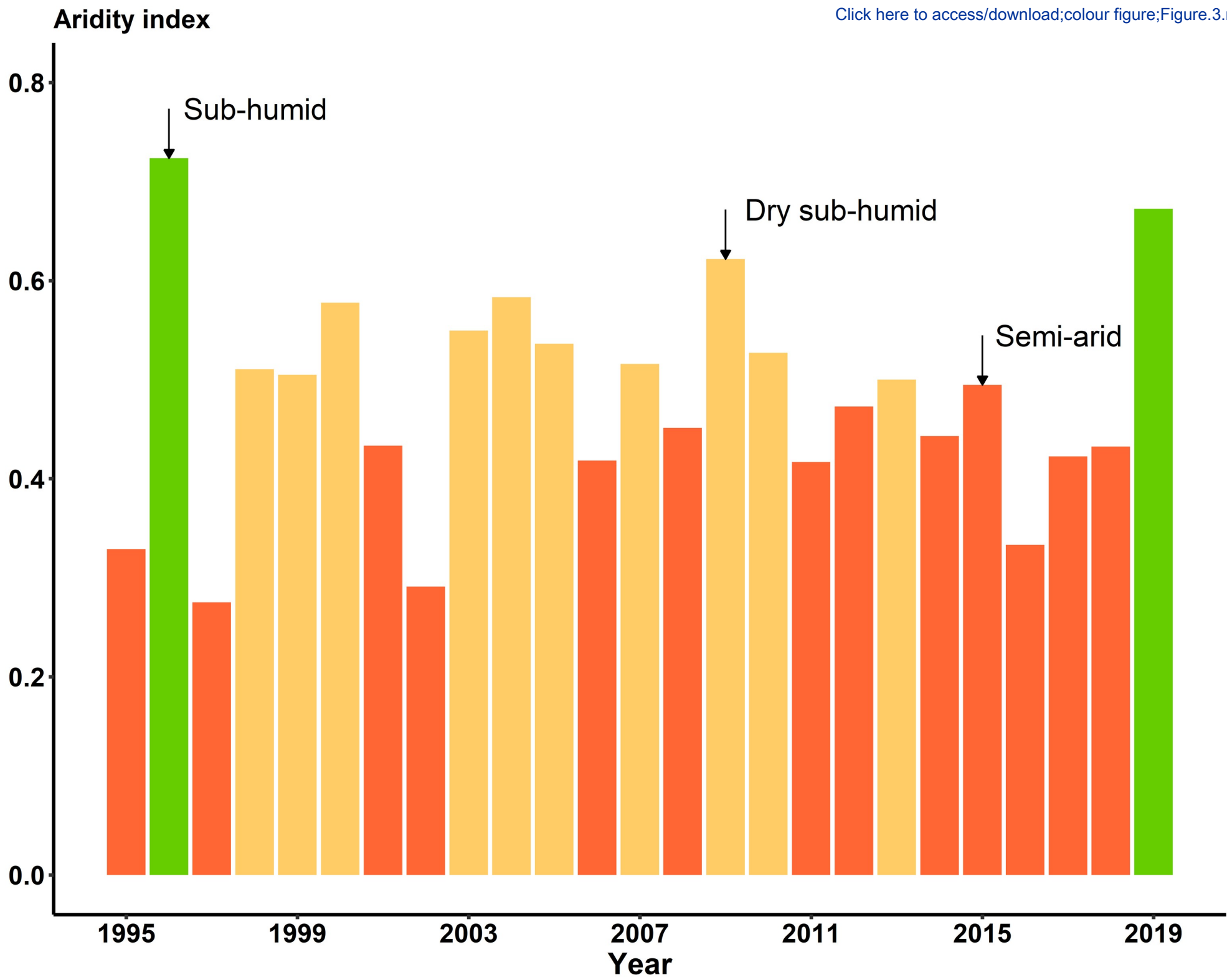




Figure 2







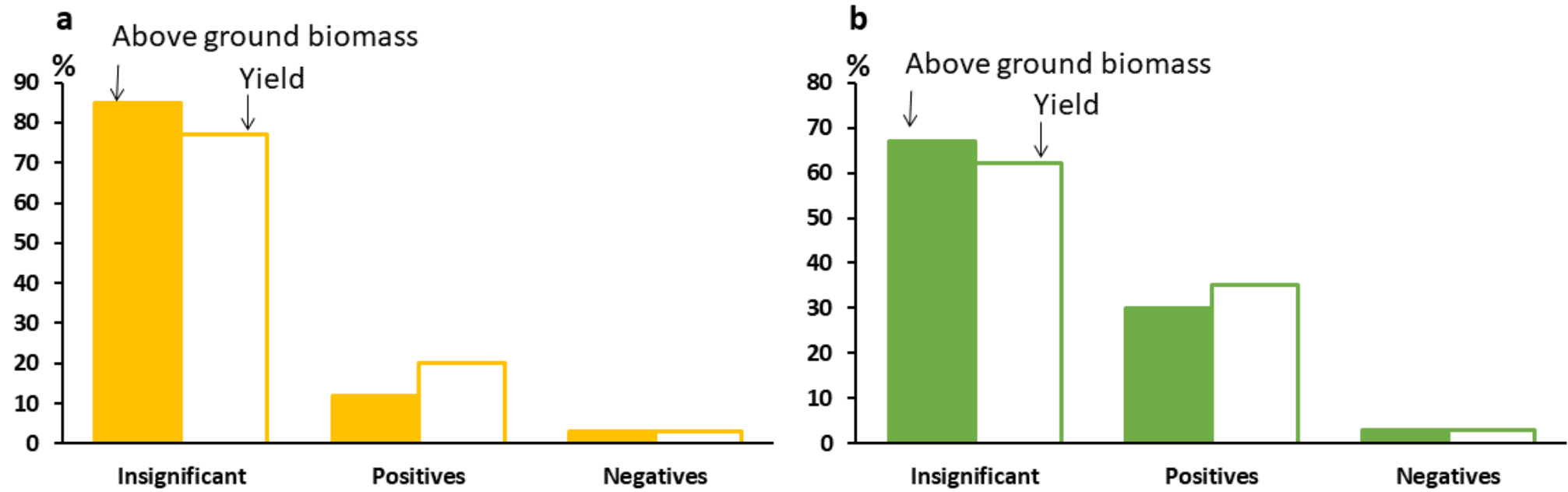


Figure 5

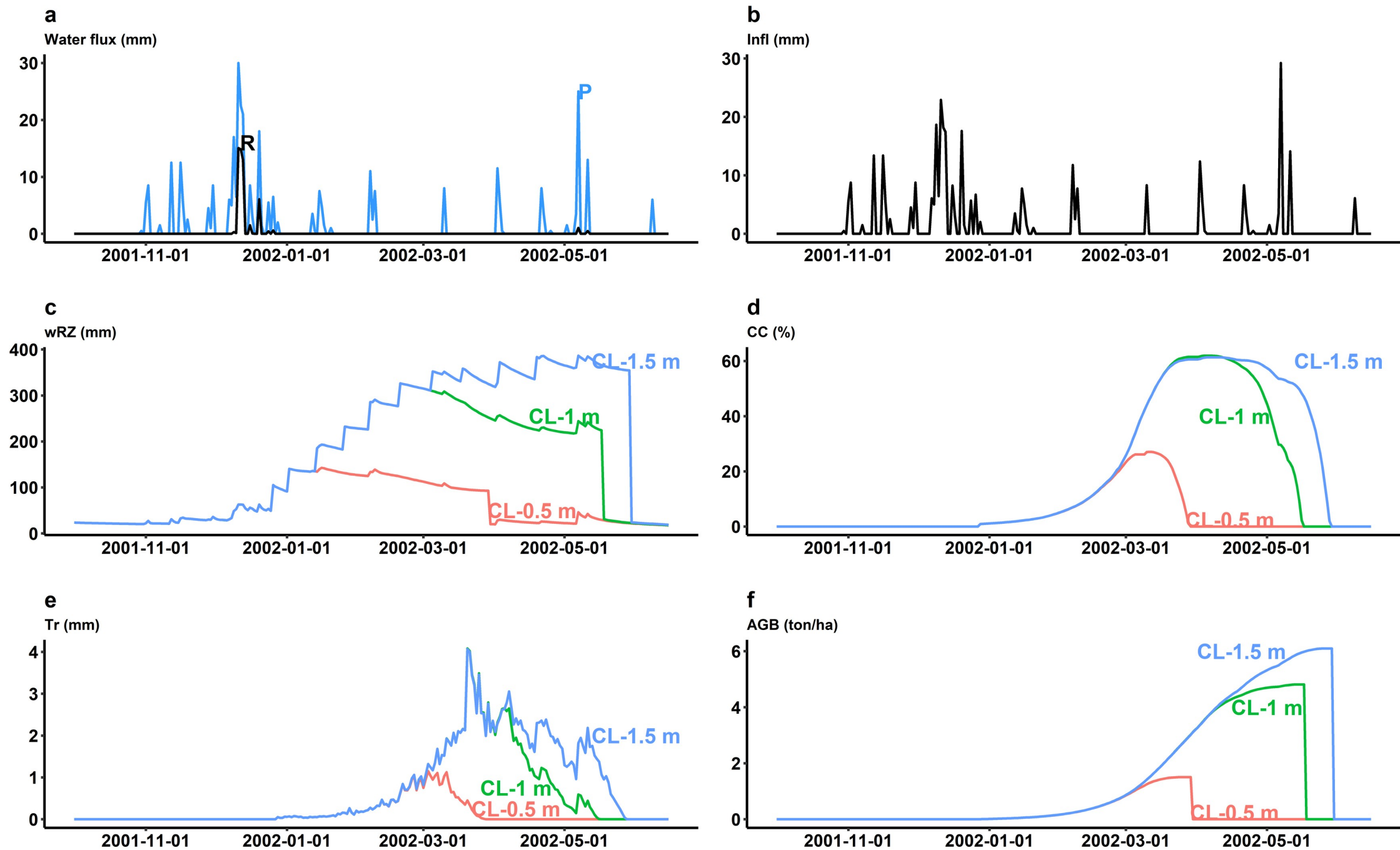
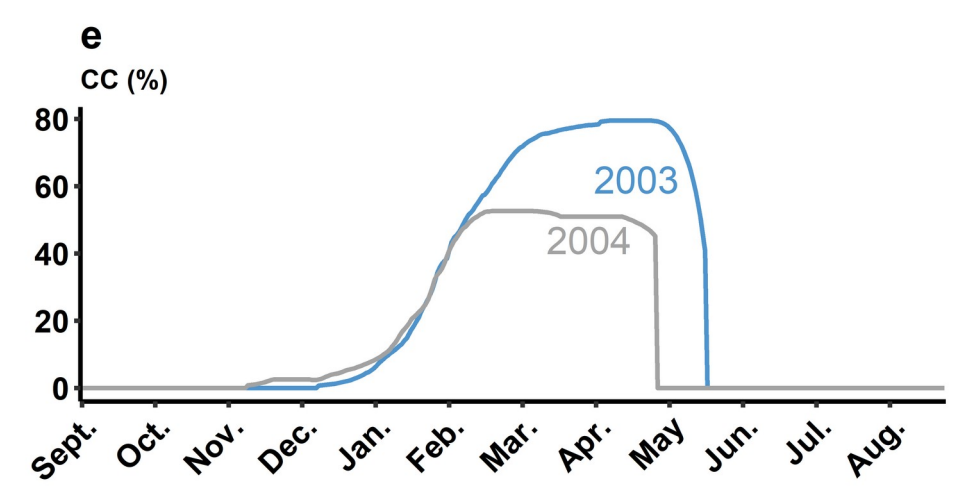
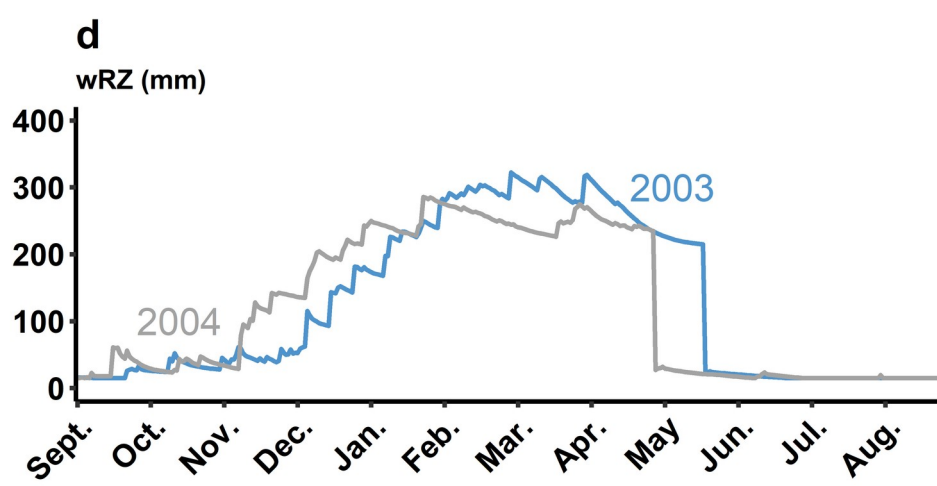
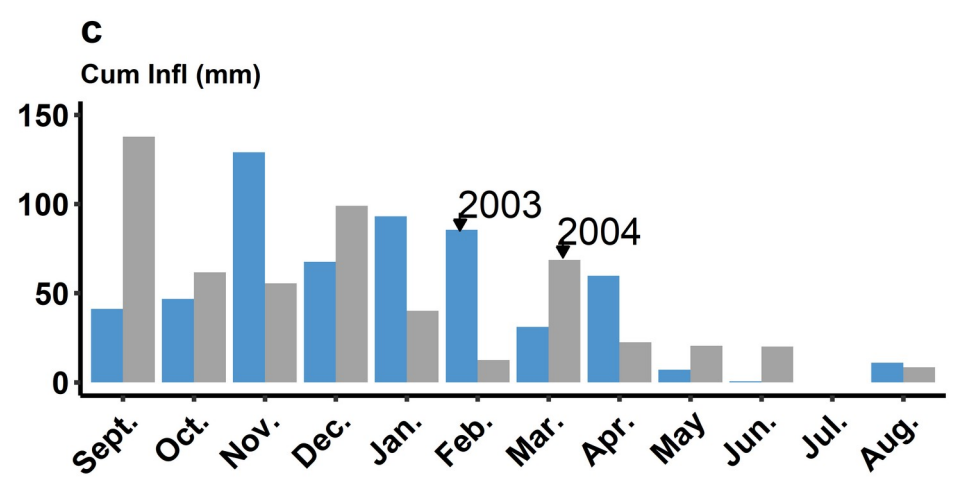
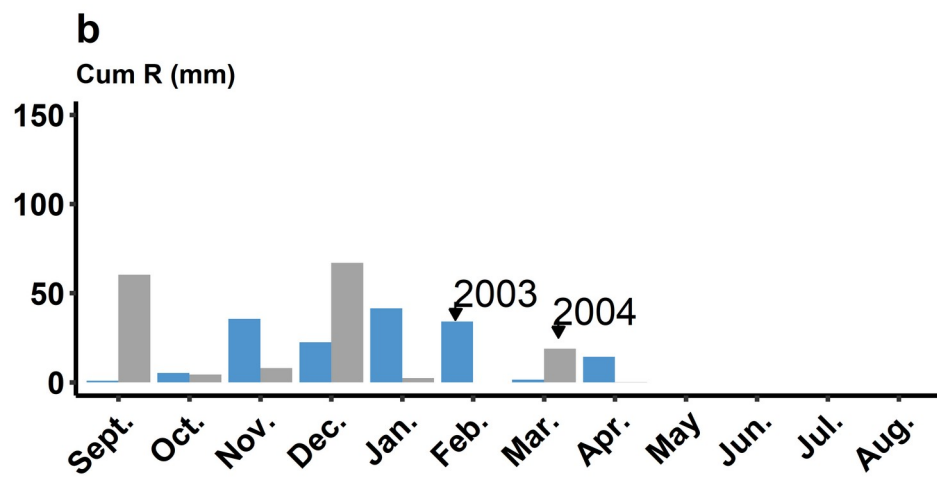
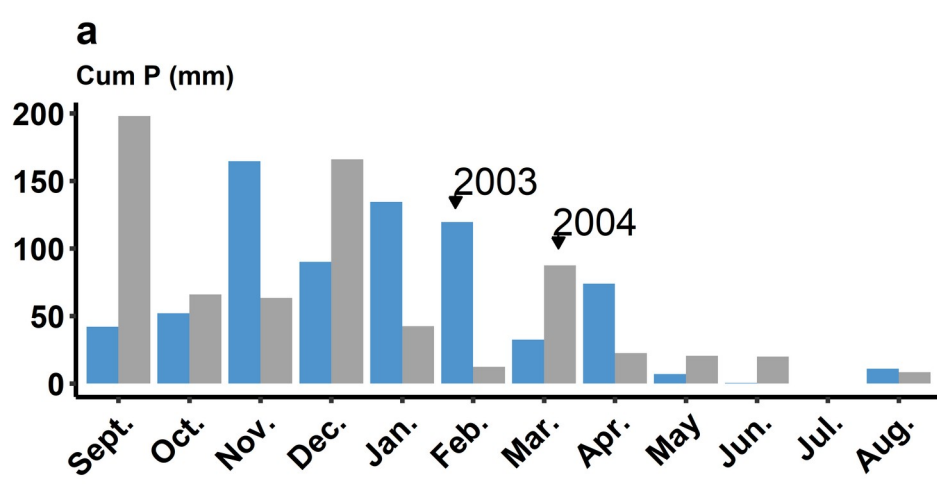


Figure 6



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**Impact of hydrological connectivity on rainfed annual crops in Mediterranean hilly  
landscapes: a numerical exploration**

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**Supplementary materials**

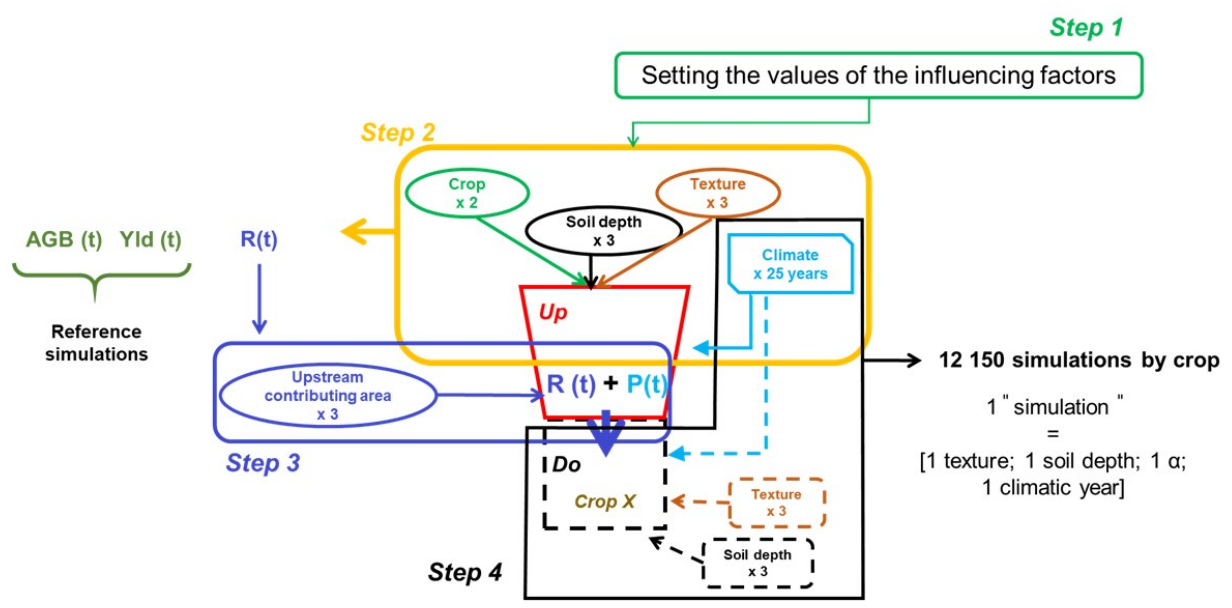
## 16 **Supplementary materials - Section 1: materials and methods - numerical experiment setting**

17 To assess the impact of hydrological connectivity on the functioning of the downstream crop, we  
18 conduct a complete numerical experiment, including all possible combinations of the environmental  
19 factors considered for both upstream and downstream plots, namely crops (wheat or faba bean), soil  
20 water content availability (derived from soil texture and depth), and climate forcing variables that drive  
21 water inputs (rainfall), water outputs (evaporative demand), and crop functioning (e.g., air temperature).  
22 This also includes combinations with the upstream runoff. The simulation plan consists of four main  
23 steps (Fig. SF 1) and results in 12 150 simulations for a given downstream crop on a yearly basis (Table  
24 ST1), and therefore, in 24 250 simulations when considering the two downstream crops.

- 25 ● Step 1: Determination of the different values of the environmental factors, detailed in Sections 2, 3,  
26 and 4 of the Supplementary Materials, except for soil parameters, which are listed in the current  
27 section (Table ST1).
- 28 ● Step 2: AquaCrop simulations without connectivity. Once the different values of the environmental  
29 factors are set, we conduct simulations on a single unconnected plot, considering all possible  
30 combinations of textures (3), soil depths (3), and crops (2) over 25 years. At the end of this step, we  
31 obtain, for each of the 18 combinations of texture/depth/crop, 25-year time series for runoff,  
32 aboveground biomass, and yield. The time series of aboveground biomass and yield are considered  
33 as reference time series (no connectivity) for assessing the impact of hydrological connectivity on  
34 crop functioning.
- 35 ● Step 3: determination of upstream runoff time series. This step involves the runoff flux simulated in  
36 Step 2, considered as a flux generated on the upstream plot that can infiltrate into the downstream  
37 plot. This runoff flux is regarded as an incoming water flux at the upper limit of the downstream  
38 plot. To account for the impluvium area, we consider three values for the upstream plot relative to  
39 the area of the downstream parcel. For this, we set the ratio of upstream to downstream plot area,  
40 labelled  $\alpha$ , to three nominal values: 0.5, 1, and 2. Then, the values within each of the 18 simulated  
41 runoff time series are multiplied by each of the three ratios  $\alpha$ , resulting in 54 simulated runoff time  
42 series that are added to rainfall on the downstream plot. At the end of this step, we obtain 54  
43 upstream runoff time series over 25 years, and we add them to the rainfall time series over 25 years  
44 for the downstream plot.
- 45 ● Step 4: AquaCrop simulations with connectivity. This step involves conducting AquaCrop  
46 simulations for the downstream plot that receives the simulated runoff from the upstream plot  
47 (Step 3). For each of the two downstream crops (wheat and faba bean) and each of the 9 situations in  
48 terms of soil water available capacity (3 soil textures and 3 soil depths), we run 54 AquaCrop  
49 simulations that include upstream runoff from Step 3. This results in  $9 \times 54 = 486$  simulations of the  
50 crop growth cycle, to be linked for further comparisons with the 9 AquaCrop simulations without  
51 connectivity (reference time series at Step 2). On a yearly basis, the 486 simulations correspond to

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486 x 25 = 12,150 simulations for each downstream crop, and thus 24,300 for both.



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**Fig. SF1:** Overview of the 4 steps for the numerical experiment plan. AGB(t), Yld(t), R(t), and P(t) represent the time series of aboveground biomass, yield, upstream runoff, and rainfall, respectively, over 25 years. 'Up' and 'Do' labels stand for the upstream and downstream plots, respectively. The 'crop X' label for the downstream plot corresponds to faba bean or wheat.

59

60 **Table ST1:** Summary of different values for the considered environmental factors at each simulation step. C, CL, and SCL stand for Clay, Clay-Loam, and Sandy-Clay-Loam  
 61 textures, respectively. Up and Do stand for upstream and downstream plots, respectively. R stands for upstream runoff. Cr, D, and T stand for crop, soil depth and texture,  
 62 respectively.  $\alpha$  stands for the ratio of the upstream to the downstream plot areas. AGB and Yld stand for aboveground biomass and grain yield. AC and SC stand for simulations  
 63 with connectivity and without connectivity, respectively.

Simulation step	Field concerned	Crop (Cr)	Soil texture (T)	Soil depth (D, m)	Upstream plot area ( $\alpha$ )	Combination number
Step 2	Field Up	{Wheat, Faba bean}	{C, CL, SCL}	{0.5, 1, 1.5}		2Cr x 3T x 3D = 18 SC simulations → 18 chronicles over 25 years for {R, AGB, Yld}
Step 3	Field Up				{0.5, 1, 2}	→ 18 chronicles of R x 3 $\alpha$ = 54 chronicles of R over 25 years
Step 4	Field Do	Wheat	{C, CL, SCL}	{0.5, 1, 1.5}	-	9 combinations {T, D} x 54 chronicles of R → 486 AC simulations over 25 years + 9 reference simulations without connectivity → 495 AC simulations over 25 years
		Faba bean	{C, CL, SCL}	{0.5, 1, 1.5}	-	9 combinations {T, D} x 54 chronicles of R → 486 AC simulations over 25 years + 9 reference simulations without connectivity → 495 AC simulations over 25 years



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## 66 **Supplementary materials - Section 2: materials and methods - choice of sowing dates and** 67 **fertilisation rates for AquaCrop**

### 68 **Choice of sowing dates**

69 The sowing date is a crucial input parameter for running AquaCrop simulations. Setting this date for  
70 each year and each crop is therefore an important step in the modelling process. An optimal sowing date  
71 allows 1) to avoid germination failure due to lack of water at the beginning of the crop growth cycle and  
72 2) to avoid the reduction of the growth time due to late sowing (Laux et al., 2010; Waongo et al., 2015).

73 We follow the sowing rules commonly set up within the study area for wheat and faba bean  
74 cultivation (expert knowledge). For a given year, the sowing date is set by respecting the following  
75 constraints.

- 76 ● The sowing period in the region: sowing must be carried out between October 20 and December 15  
77 for wheat and between early November and late December for faba bean.
- 78 ● Cumulative rainfall since the beginning of the rainy season: the first date is chosen so that the  
79 cumulative rainfall (calculated from September 1) is equal to or greater than 200 mm.
- 80 ● The daily rainfall amount on the chosen date: the sowing date is postponed by 5 days if the daily  
81 cumulative rainfall on the chosen date is very high (exceeds 20 mm).

### 82 **Fertilisation rate**

83 For wheat fertilisation, we follow Dhouib et al. (2022) who set to 25% the value of fertilisation stress.

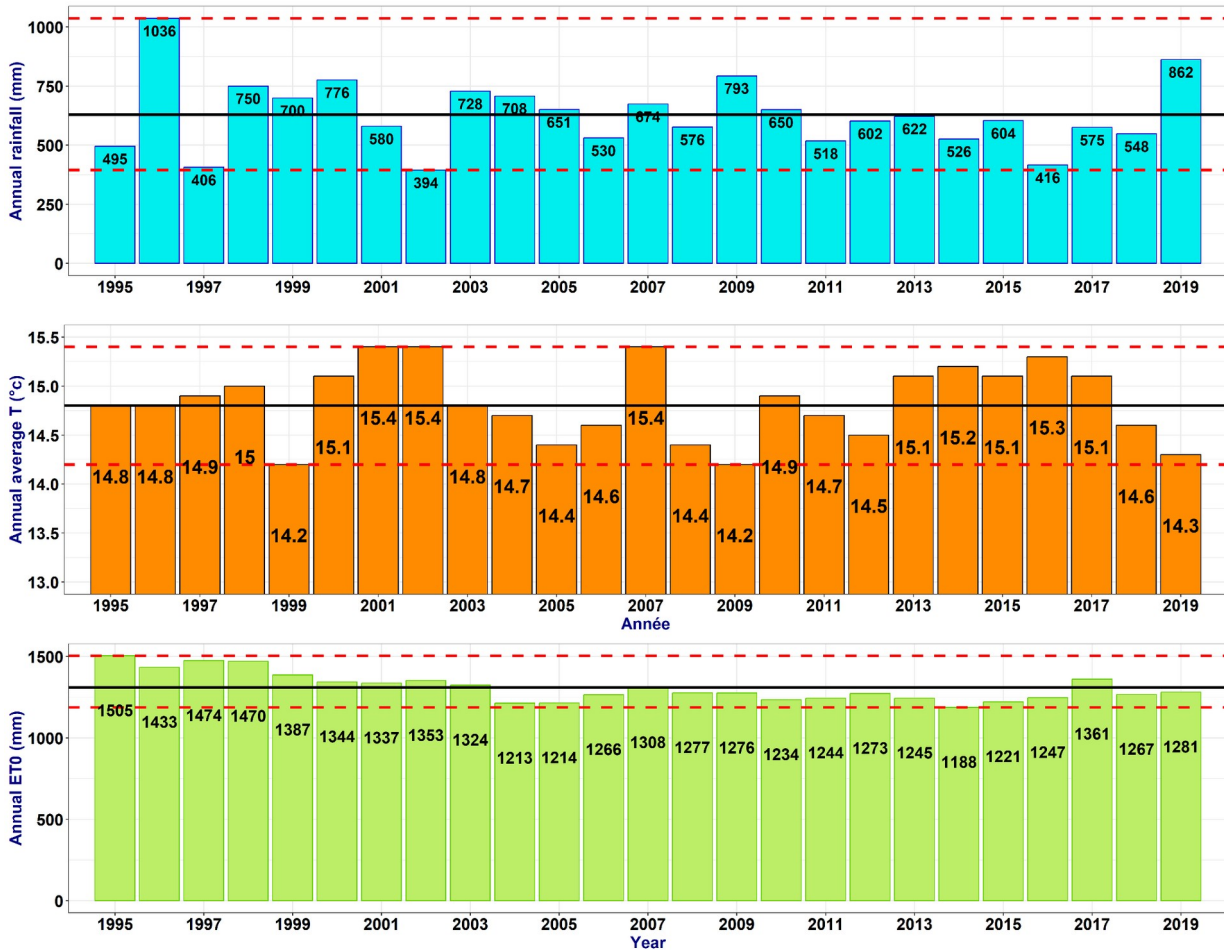
84 For faba bean, being a nitrogen-fixing legume, no fertilisation is necessary.

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86 **Supplementary materials - Section 3: materials and methods - climate forcing variables**

87 **Times series of climate variables**

88



89

90 **Fig. SF2:** annual cumulative rainfall (1st row), annual average temperature (2nd row), and reference  
 91 evapotranspiration (ET<sub>0</sub>) (3rd row). Annual average temperatures (T) are calculated from October to May,  
 92 corresponding to the growing season at the regional scale. The solid black line represents the average of each  
 93 variable over the 25 years, and the dashed red lines represent the maximum and minimum cumulative values over  
 94 the 25 years.

95 **Classification of climate conditions**

96 We characterise the annual climate using an aridity index, which serves as a proxy for soil water  
97 availability according to soil-atmosphere exchanges (Nastos et al., 2013). We use the aridity index  
98 proposed by FAO (FAO AI). This index expresses the degree of aridity as the ratio of the annual  
99 cumulative rainfall P to the annual cumulative reference evapotranspiration  $ET_0$  (Spinoni et al., 2015):

$$FAOAI = \frac{P}{ET_0} \quad (\text{SE 1})$$

100 The classification of climate years according to FAO AI is provided in Table ST3.

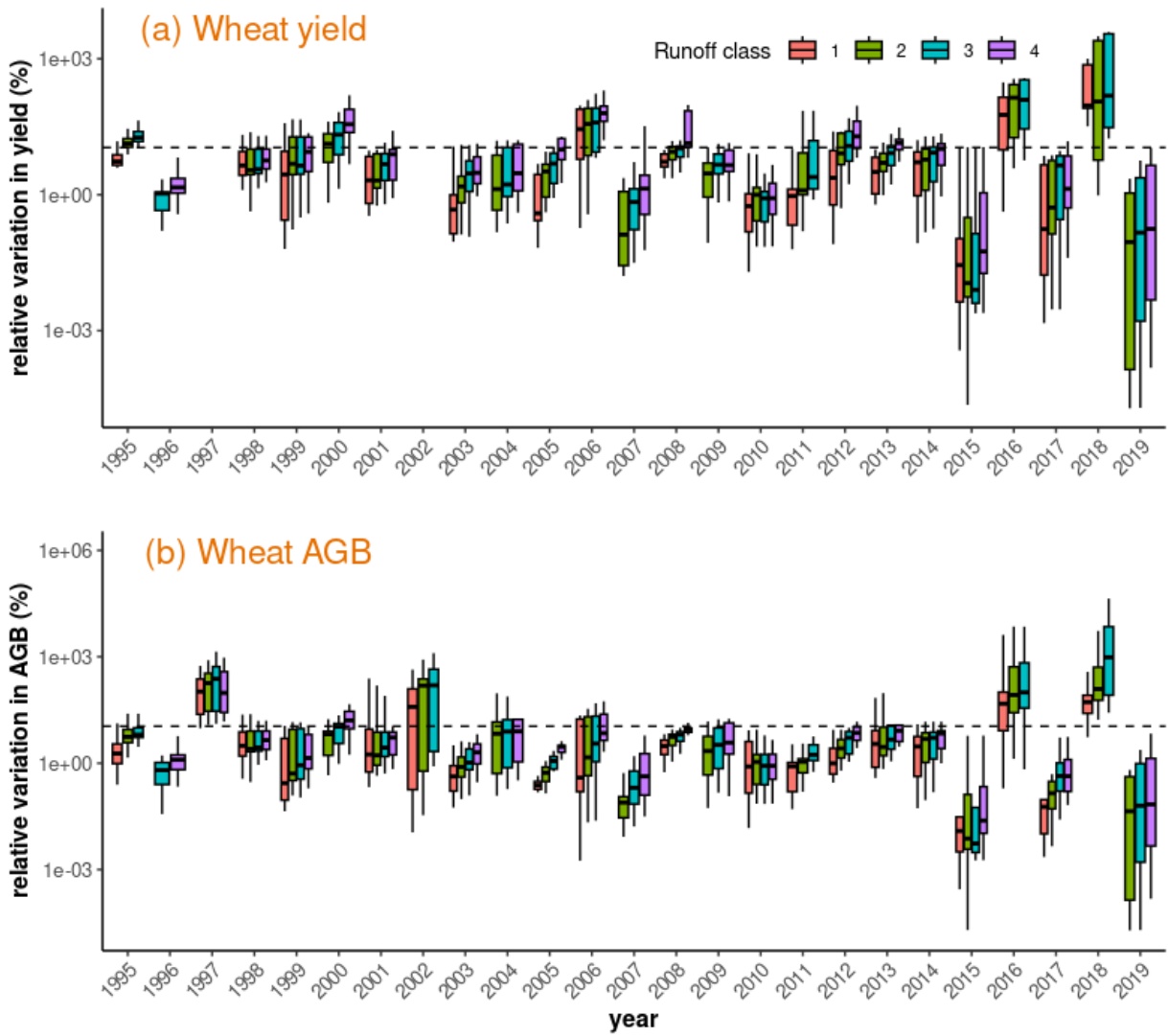
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102 **Table ST2:** Aridity classification according to the FAO index.

<b>FAO AI</b>	<b>Climate Class</b>
[0.00 - 0.03[	Desertic
[0.03 - 0.05[	Hyper-arid
[0.05 - 0.20[	Arid
[0.20 - 0.50[	Semi-arid
[0.50 - 0.65[	Dry sub-humid
[0.65 - 0.75[	Sub-humid
[0.75 - 1.50[	Humid
$\geq 1.50$	Hyper-Humid

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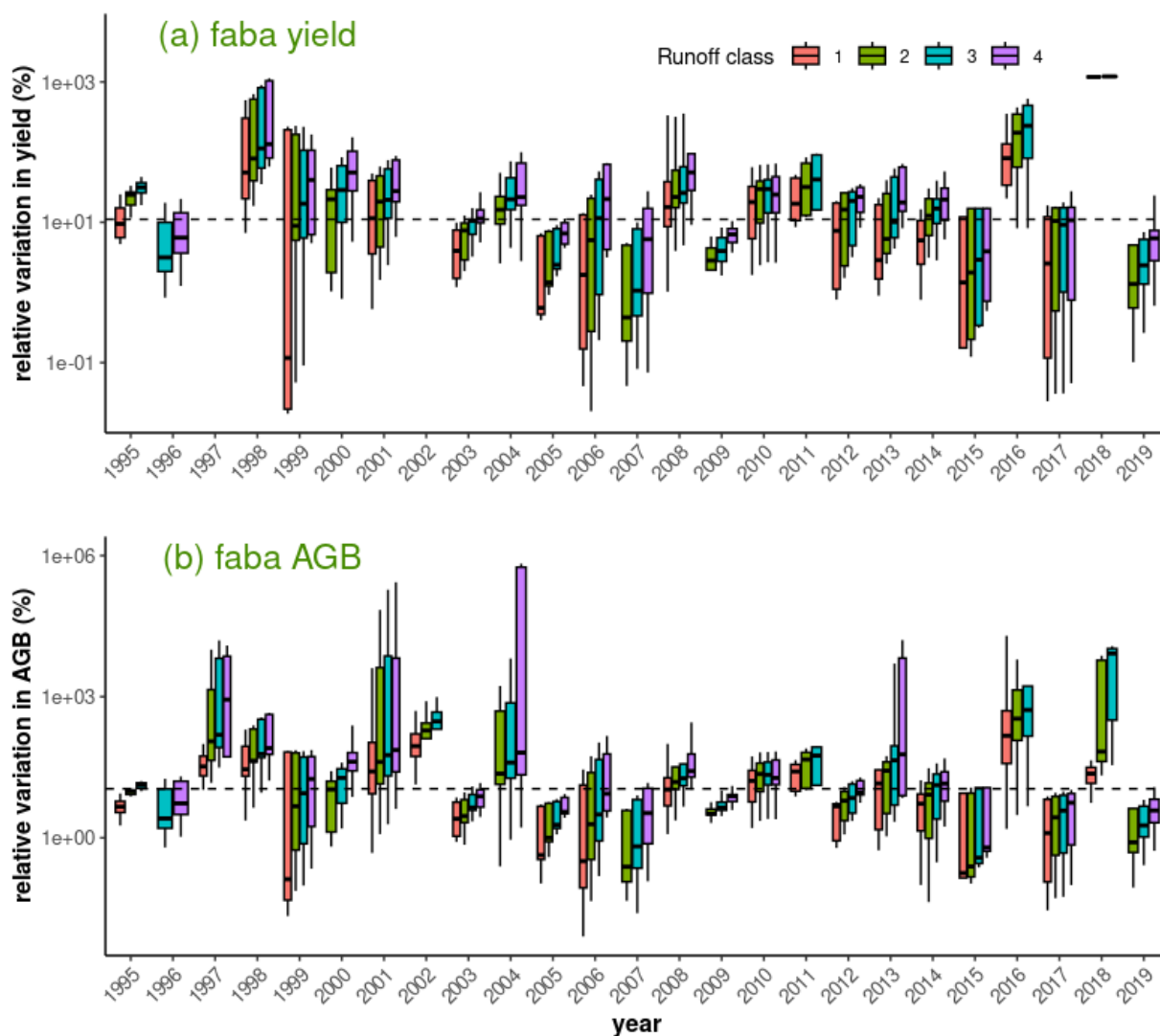
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107 **Fig. SF3:** Relative variation (%) in yield (Yld) and Above Ground Biomass (AGB) over the 25-year  
108 period for wheat crop considering each runoff class. The dashed line represents the level of significant  
109 relative variation established in the study.

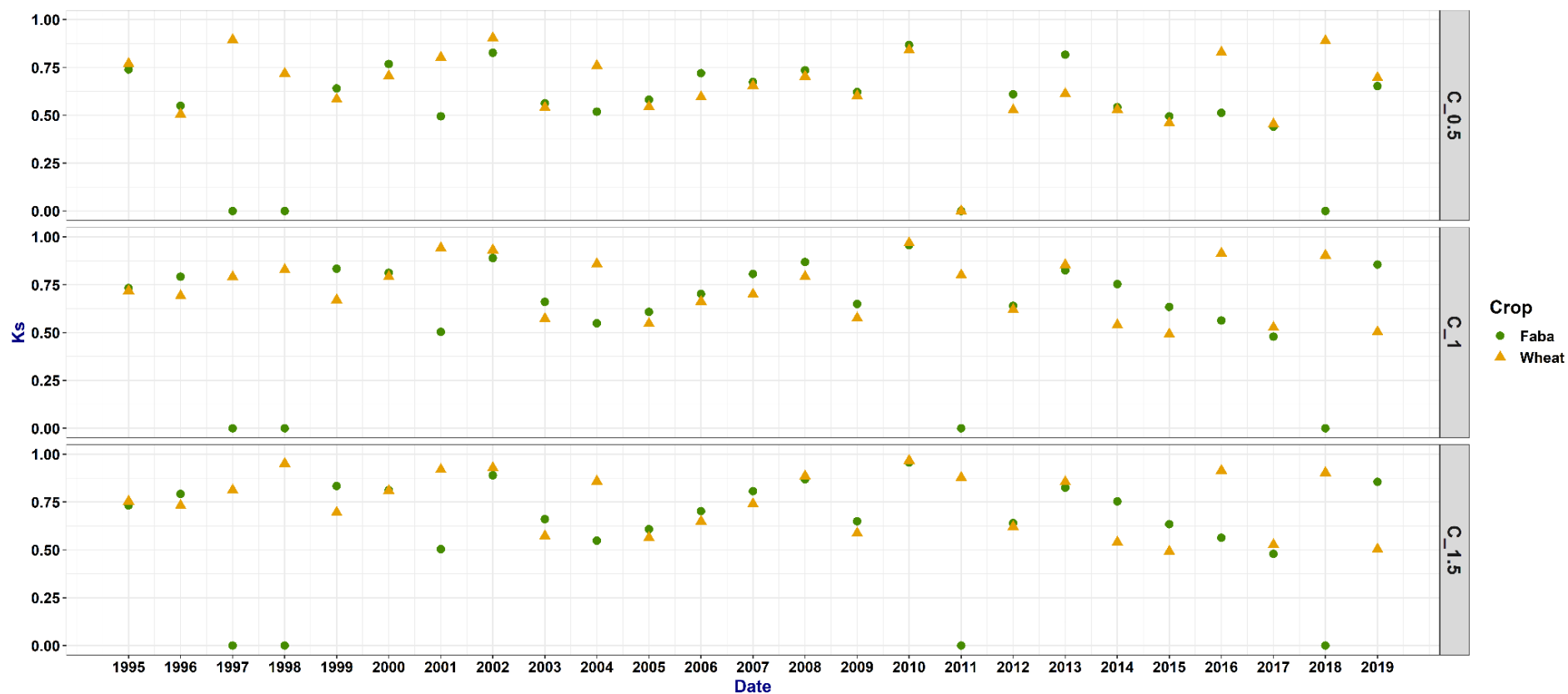
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113 **Fig. SF4:** Relative variation (%) in yield (Yld) and Above Ground Biomass (AGB) over the 25-year  
114 period for faba crop considering each runoff class. The dashed line represents the level of significant  
115 relative variation established in the study.

116 **Supplementary materials - Section 5: results and discussion - water stress coefficient Ks**



117

118 **Fig. SF5 (part 1/3):** Mean water stress coefficient (Ks), calculated for faba bean (green disks) and wheat (yellow triangles) when considering simulations without connectivity.

119 A Ks equal to 1 corresponds to no water stress, while a Ks equal to 0 corresponds to full water stress. C represents Clay texture, respectively. The labels “\_0.5”, “\_1”, and

120 “\_1.5” denote soil depths of 0.5 m, 1 m, and 1.5 m, respectively.

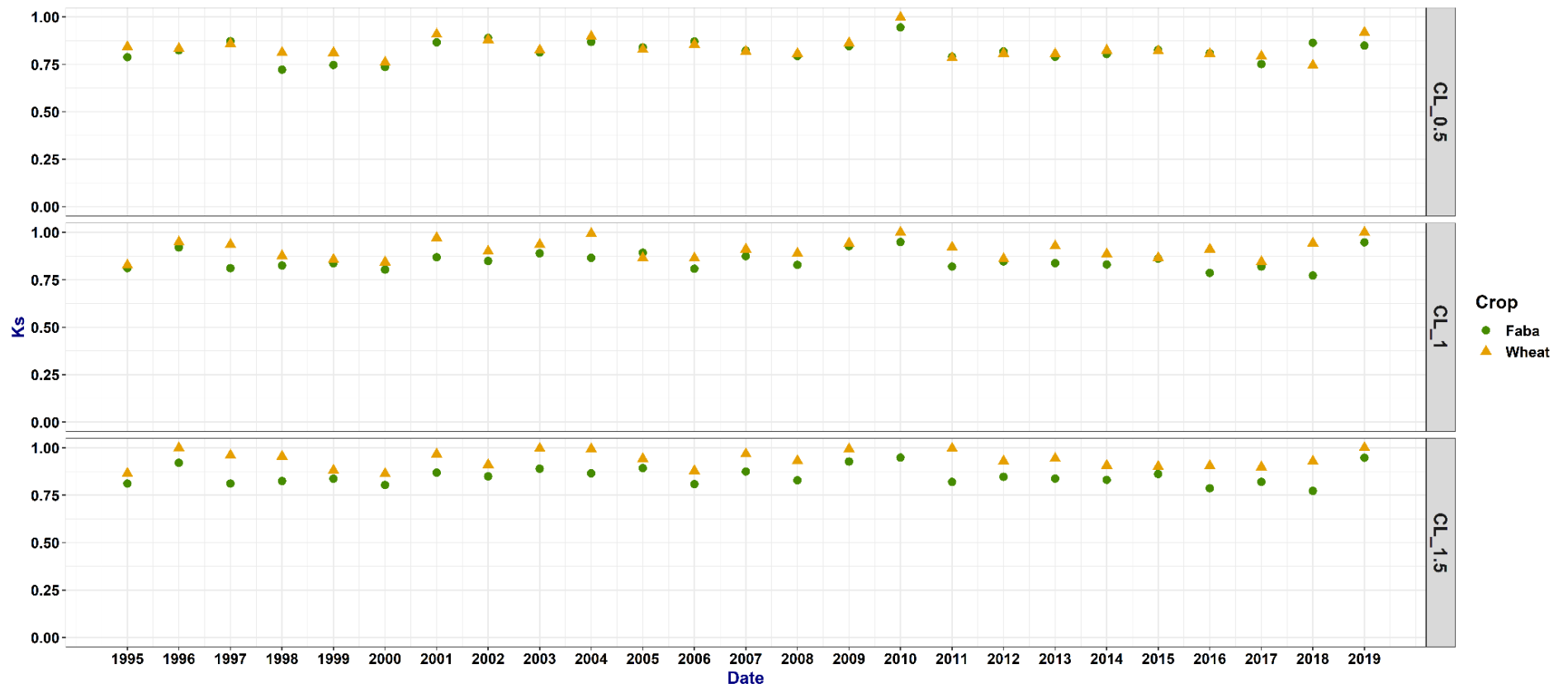
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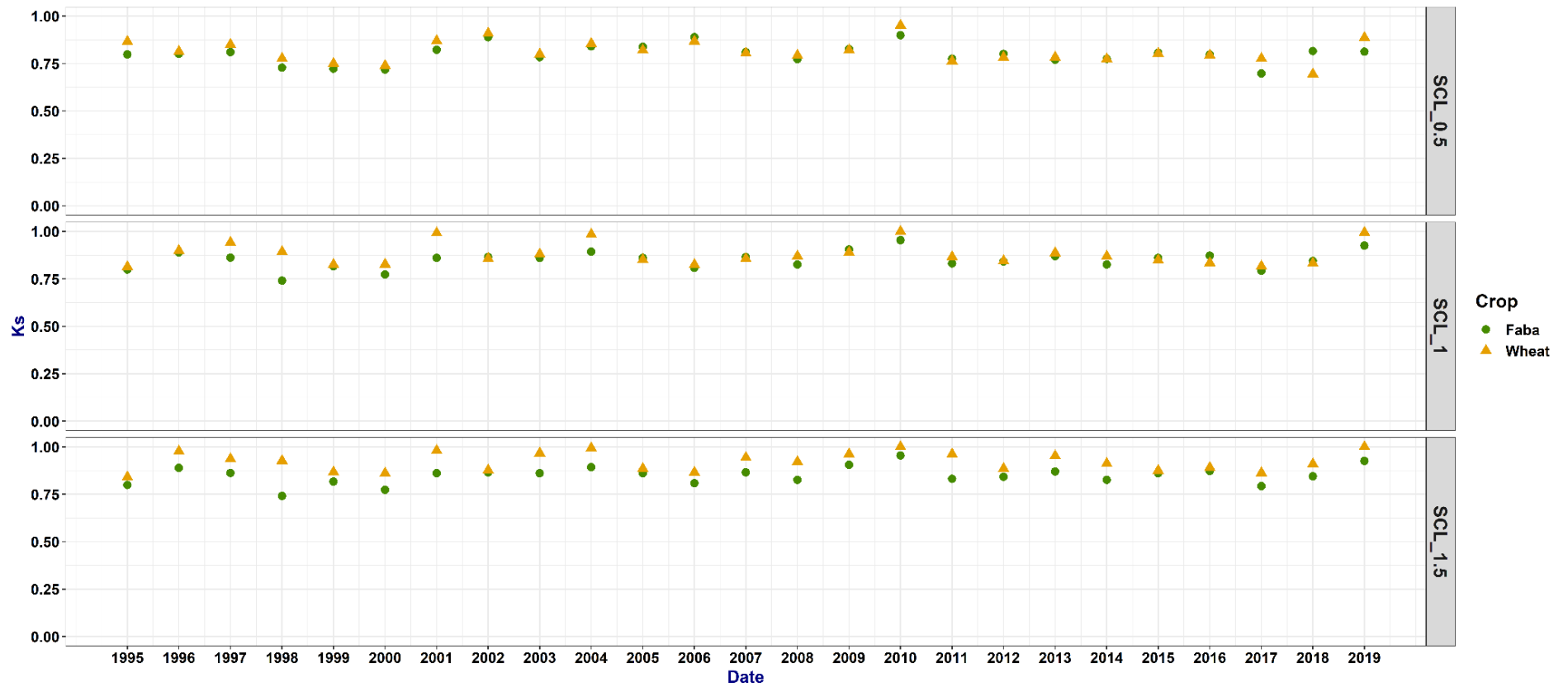
124 **Fig. SF5 (part 2/3):** Mean water stress coefficient (Ks), calculated for faba bean (green disks) and wheat (yellow triangles) when considering simulations without connectivity.  
125 A Ks equal to 1 corresponds to no water stress, while a Ks equal to 0 corresponds to full water stress. CL represents Clay-Loam texture, respectively. The labels “\_0.5”, “\_1”,  
126 and “\_1.5” denote soil depths of 0.5 m, 1 m, and 1.5 m, respectively.

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129 **Fig. SF5 (part 3/3):** Mean water stress coefficient (Ks), calculated for faba bean (green disks) and wheat (yellow triangles) when considering simulations without connectivity.  
 130 A Ks equal to 1 corresponds to no water stress, while a Ks equal to 0 corresponds to full water stress. SCL represents Sandy-Clay-Loam texture. The labels “\_0.5”, “\_1”, and  
 131 “\_1.5” denote soil depths of 0.5 m, 1 m, and 1.5 m, respectively.

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132 **Supplementary materials - Section 6: results and discussion - Influence of environmental**  
 133 **condition**

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135 **Table ST3:** Percentage occurrence of (1) insignificant relative differences ( $-0.11 < \Delta < 0.11$ ) and (2) significant  
 136 and positive relative differences ( $\Delta > 0.11$ ) categorised by upstream runoff classes. The labels R1, R2, R3, and  
 137 R4 correspond to upstream runoff classes 1, 2, 3, and 4, respectively.

<b>Impact of hydrological connectivity</b>	<b>Crop</b>	<b>Variable</b>	<b>R1</b>	<b>R2</b>	<b>R3</b>	<b>R4</b>
<b>Insignificant impact</b>	Wheat	AGB	26	25	25	24
		Yld	27	26	24	23
	Faba bean	AGB	29	26	23	22
		Yld	30	26	23	21
<b>Positive impact</b>	Wheat	AGB	22	24	27	27
		Yld	16	25	30	29
	Faba bean	AGB	17	23	30	30
		Yld	18	24	28	30

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139 **Table ST4:** Average of relative difference calculated for infiltration (Infl), soil water content (SWC)  
 140 and root zone water content (wRZ), for situations with positive impact and insignificant impact of hydrological  
 141 connectivity. Relative differences correspond to differences between simulations with and without connectivity,  
 142 and are next averaged over all situations (25 years, 54 upstream runoff, 9 downstream soil conditions). Infl is  
 143 calculated over the hydrological year while SWC and wRZ are calculated over the crop growth cycle.

<b>Impact</b>	<b>Crop</b>	<b>Relative differences (%)</b>		
		<b>Infl</b>	<b>SWC</b>	<b>wRZ</b>
<b>Positive impact</b>	Wheat	10%	4%	41%
	Faba bean	7%	4%	24%
<b>Insignificant impact</b>	Wheat	8%	2%	2%
	Faba bean	6%	2%	1%

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146 **Table ST5:** Average of relative difference calculated for infiltration (Infl), soil water content (SWC) and root  
 147 zone content water (wRZ), for both situations with positive impact and insignificant impact of hydrological  
 148 connectivity, in semi-arid (SA) and dry sub-humid (DSH) years. Relative differences correspond to differences  
 149 between simulations with and without connectivity, and are next averaged over all situations (number of years  
 150 for SA or DSH class, 54 upstream runoff, 9 downstream soil conditions). Infl is calculated over the hydrological  
 151 year while SWC and wRZ are calculated over the crop cycle.

Climate year	Impact	Crop	Relative differences (%)		
			Infl	SWC	wRZ
SA	Positive impact	Wheat	9%	4%	29%
		Faba bean	7%	4%	18%
	Insignificant impact	Wheat	8%	2%	2%
		Faba bean	5%	2%	1%
DSH	Positive impact	Wheat	10%	4%	58%
		Faba bean	7%	4%	32%
	Insignificant impact	Wheat	9%	2%	2%
		Faba bean	6%	2%	1%

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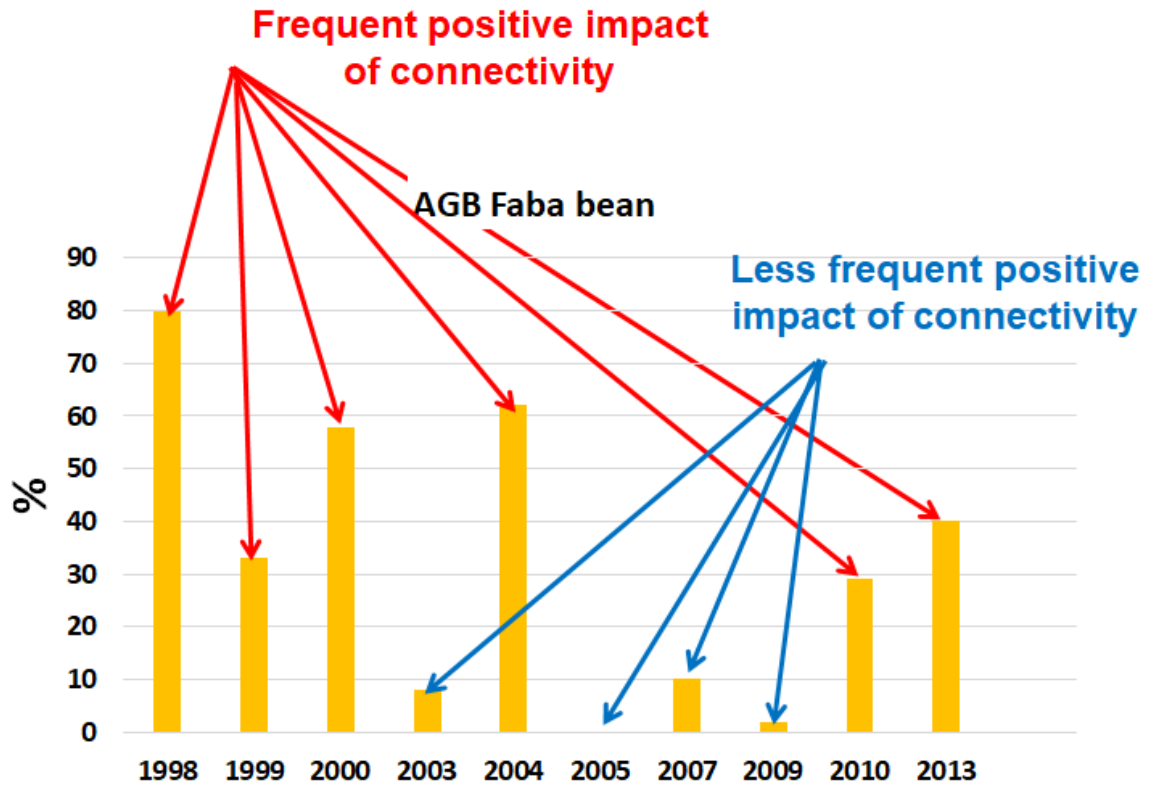
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164 Fig. SF6: Occurrence in dry sub-humid years of positive impact ( $\Delta > 0.11$ ) for faba bean.

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