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1 Performance of wheat-based cropping systems and economic  
2 risk of low relative productivity assessment in a sub-dry  
3 Mediterranean environment

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10  
11 **Abstract**

12 The promotion of optimum rotations and agricultural management of winter wheat-based  
13 cropping systems is very critical, as wheat is considered an essential component in the  
14 Mediterranean diet. Considering the delicate economic situation of farmers in the  
15 Mediterranean area, recommending a low risk, sustainable farming system is desirable. In  
16 this study, an innovative application of a multi-criteria field-level approach is presented,  
17 targeting food security, farmer profitability and environmental sustainability. The  
18 CropSyst biophysical simulation model was calibrated and implemented for the study site.  
19 It was chosen for its agro-environmental robustness to simulate four rotations (wheat-  
20 wheat, wheat-fallow, wheat-potato, and wheat-fava bean). Four types of wheat agricultural  
21 management systems (full fertilization and full irrigation, full fertilization and zero  
22 irrigation, zero fertilization and full irrigation, and zero fertilization and irrigation) were  
23 tested in low and high soil water holding capacity (WHC) types. The effects of soil  
24 conditions, management practices and rotation type on wheat grain yields were assessed.  
25 Furthermore, the performance of each winter wheat-based cropping system was evaluated  
26 in terms of productivity (protein production and profitability) and the efficient use of

27 resources (nitrogen and water), as well as the economic risk of low relative productivity  
28 each one engenders. The results show that there is no particular optimal scenario that can  
29 simultaneously ensure high productivity, reduce economic risk of low relative productivity,  
30 and achieve high wheat- water- and nitrogen-use efficiency. However, the wheat-fava bean  
31 rotation cultivated with no wheat fertilization appeared to be a better substitute to the  
32 wheat-wheat rotation in terms of protein production (0.93 t/ha versus 0.8 t/ha in low WHC  
33 soil and 1.34 t/ha versus 1.17 t/ha in high WHC). This cropping system achieved a higher  
34 net profit (2111 US\$/ha versus 1222US\$/ha in low WHC and 3550 US\$/ha versus 2450  
35 US\$/ha in high WHC), showing high resource-use efficiency and was less risky for  
36 farmers. Moreover, a very high profit could only be attained with the wheat-potato rotation  
37 (8640 US\$/ha and 12170 US\$/ha in low and high WHC, respectively), yet with low input-  
38 efficiency and high economic risk of low relative productivity.

39 *Keywords:* Winter wheat, CropSyst, Risk, Efficiency, Management, Cropping system,  
40 Lebanon.

41

## 42 **1. Introduction**

43 Throughout history, the Mediterranean, especially its eastern and southern parts, has been  
44 known to be the origin of many landraces and a pioneer in food production. It has never  
45 been a region of abundance and glut, yet has always overcome the deficiencies in  
46 production (Braudel, 1990; Kehoe, 1988). Winter wheat (*Triticum Durum L.*) is one of the  
47 major crops grown in the Mediterranean. In Lebanon and the Middle East and North Africa  
48 (MENA) region, wheat is often financially and sometimes technically supported as a part  
49 of the governmental subsidy system. This self-sufficiency policy has long been the bedrock

50 of food security, leading to the continuous cultivation and successive sowing of wheat (El  
51 Khansa, 2017; Nasrallah et al., 2018). At the same time, the MENA region is the largest  
52 cereal importer in the world, with over 58 million metric tons, covering more than 50% of  
53 its consumption (Wright and Cafiero, 2010). For nations within the MENA region,  
54 importing cereal grains (mainly wheat) is not a matter of choice, but a necessity (Ahmed  
55 et al., 2014).

56 Even if policies and policy-makers are keen to encourage large cereal production (wheat  
57 in particular), simple wheat-based cropping systems co-exist in the Mediterranean region  
58 (MoA, 2010). Intensive local wheat production in monoculture (wheat-wheat rotations) has  
59 always been coupled with drawbacks and nutrient mining and deficiency. According to  
60 Sieling et al. (2005), wheat-following-wheat rotations indeed lead to reduced yields,  
61 compared to wheat following a different crop. The main reasons behind this finding are (1)  
62 the increase in biotic yield-limiting factors (Bennett et al., 2012) and (2) a lesser availability  
63 of needed nutrients and particularly nitrogen (Dalal et al., 2001; Sieling et al., 2005).  
64 Thereby, the different already existing wheat-based cropping systems (with different  
65 rotation and management practices) are directly linked to soil water and nitrogen access  
66 (Pala et al., 2007; Ryan et al., 2007), production type (e.g. cereal grains, legume grains or  
67 vegetables), in addition to economic risk, which farmers can overcome (Komarek et al.,  
68 2015; Sadras, 2002).

69 Thus, several studies have tried to address the obvious question of the performance and  
70 outputs of each production system. Diverse crop rotations have been experimented, and  
71 sometimes versus monoculture systems (Beaudoin et al., 2005; Constantin et al., 2010;  
72 Hansen et al., 2015, 2010; Macdonald et al., 2005; Moreau et al., 2012; Sieling and Kage,

73 2006). For instance, long-term field experiments in Central and Western Europe have  
74 shown that the inclusion of a catch crop within a rotation can indeed significantly increase  
75 nitrogen-use efficiency (NUE) as well as the N (Nitrogen) uptake of the main crop  
76 (Berntsen et al., 2006; Constantin et al., 2011). In comparing different types of wheat-based  
77 rotations, Angus et al. (2015) found that both fallow-wheat and break crop-wheat rotations  
78 generally produced greater yields than wheat-wheat rotations. For instance, legume-wheat  
79 rotations generated over 20% wheat grain yields compared to wheat-wheat rotations.  
80 Without underestimating the role of plant genetics, the efficient management of water and  
81 N has been identified as a crucial need for closing the yield gap, which is estimated by  
82 comparing the observed yield with the attainable one (Mueller et al., 2012), of main cereal  
83 crops (Sinclair and Rufty, 2012) notably on arid and semi-arid soils with low organic  
84 carbon and nitrogen content (Darwish et al., 2018). Downscaling to field and farm levels  
85 made it possible to study and analyse the economic risk that farmers and producers could  
86 face, in relation to their adopted cropping systems (Di Falco and Perrings, 2005; Komarek  
87 et al., 2015; Mahmood et al., 2017; Valle et al., 2004). However, the absence of a clear  
88 integrated approach at field level, assessing different existing wheat-based cropping  
89 systems regarding their productivity, resource-use efficiency and economic risk of low  
90 productivity, represent the motivation of this study. It raises the key issue of the wheat-  
91 based cropping systems to be promoted (regarding resources, soil types, climatic  
92 variability, and management systems). It also offers a conceptual guide-map, allowing  
93 policy-makers and producers to categorize different cropping systems with reference to  
94 productivity (i.e. net profit and protein production), efficiency (water and nitrogen) and the  
95 economic risk of low relative productivity.

96 For this purpose, the biophysical simulation model "CropSyst" version 3 (Monzon et al.,  
97 2012) was calibrated and evaluated in the mid-Bekaa plain in Lebanon based on extensive  
98 field work. Scenarios concerning different existing wheat-based cropping systems (rotation  
99 type and wheat management system) in two soil types with contrasting water holding  
100 capacities were developed and run against historical long-period climatic data (i.e. 20  
101 years). Based on the model outputs, the objectives of the paper were to first, to measure  
102 and compare the effect of the different rotations (wheat-wheat, wheat-potato, wheat-fallow  
103 and wheat-fava beans) and agricultural practices (water and nitrogen) on winter wheat  
104 grain yield. Second, to evaluate and compare the performance of each cropping system (of  
105 rotation type and agricultural practices) in terms of productivity and efficiency of utilizing  
106 the resources. Finally, to establish the link between the performance of each cropping  
107 system and its economic risk of low relative productivity.

## 108 **2. Methods**

### 109 **2.1. Study site and crop management**

110 The Bekaa plain in Lebanon is located between 33°33' N and 33°60' N latitude, 35°39' E  
111 and 36°14' E longitude (Fig. 1). The area of the plain is around 860.25 km<sup>2</sup> with an average  
112 elevation of 1000 m above sea level. The dominant soils within the plain are mainly clay  
113 to loam but differ in their water holding capacity (WHC). The Bekaa is characterized by a  
114 semi-arid Mediterranean climate and the average annual precipitation is around 600 mm.  
115 In addition, agriculture is the main economic activity as field crops, orchards, annual and  
116 perennial plants are cultivated.

117

118 Field crop areas (e.g. cereals, vegetables, alfalfa and legumes) range from 0.1 ha to 20 ha.  
119 65% of the national cereal production is produced in the Bekaa plain, while winter wheat  
120 areas in the plain correspond to 44% of the national wheat area, occupying areas ranging  
121 from 9000 to 12000 ha annually. 51% of potato crops, which is one of the largest tuberous  
122 crops cultivated in Lebanon, is cultivated in the Bekaa plain as one of the most important  
123 cash crops. As for legumes, Bekaa is responsible for 20% of the national cultivation area,  
124 16% of this area corresponds to fava beans, which occupy around 1548 ha in the plain  
125 (MoA, 2010). Wheat and fava beans are winter crops, as they are sown in November, while  
126 potatoes are sown in March.

127 Regarding irrigation management, 72% of Bekaa crops are fully or supplementary  
128 irrigated. Even though fava beans and wheat are grown during the winter season, they  
129 receive supplementary irrigation during early spring to ensure better yields, although 20%  
130 of the wheat in the Bekaa plain is not supplementary irrigated (due to no access to water,  
131 money shortage and/or in the hope of a good rainy season) (El Khansa, 2017). While  
132 potatoes, on the other hand, are fully irrigated (on a weekly basis) from sowing to  
133 harvesting, ranging from 10 to 20 mm per application, depending on the phenological stage  
134 (Darwish et al., 2003, 2006a).

135 Fertilization is supplied, especially nitrogen, being one of the most growth driving nutrient.  
136 Fertilization management practices differ among farmers, however, nitrogen is supplied in  
137 both organic and inorganic forms. In the case of wheat, farmers supply nitrogen in amounts  
138 of up to 230 kg ha<sup>-1</sup> as ammonium sulfate at emergence and before the flowering stages.  
139 However, up to 15% of wheat farmers do not apply synthetic fertilization. This is mainly

140 due to the cultivation of potato as a previous crop, where the land is supposed to be fertile  
141 enough to meet wheat nitrogen demands, besides other economic considerations and  
142 money saving purposes, when necessary. As for potato crops, nitrogen is applied before  
143 planting in the form of manure (around 250 kgN ha<sup>-1</sup>), in addition to a second application  
144 of nitrogen (around 100 kgN ha<sup>-1</sup>) before the inception of flowering. When fertilized, fava  
145 beans receive a triggering amount of 50 kgN ha<sup>-1</sup> of nitrogen 60 days after sowing.

146 In the Bekaa plain, one of the most followed rotation types is the wheat-potato rotation as  
147 it is one of the most profitable rotations. In fact, the existence of wheat-legume rotations is  
148 limited within the Bekaa plain. However, some farmers do cultivate wheat in monoculture  
149 to benefit from governmental support in buying their harvest with relatively good prices.  
150 23% of wheat cultivated land in 2016 had also been wheat cultivated in 2017 (Nasrallah et  
151 al., 2018). Therefore, among suitable agriculture land, less than 1500 ha of land are left as  
152 fallow annually, corresponding to 4% of the total exploited area.

153

## 154 **2.2.Simulation model**

### 155 **2.2.1. CropSyst model description**

156 The CropSyst model, which was first presented by Stockle et al. (2003, 1994), uses  
157 weather, soil and crop input data for the estimation of crop productivity under different  
158 management conditions (water and nutrient input). It has been widely applied to many  
159 regions (e.g. USA, China, Central and Northern Europe and the Mediterranean) and crops  
160 (e.g. cereals, vegetables and legumes) (Ahmad et al., 2017; Belhouchette et al., 2008;  
161 Brooks et al., 2017; Palosuo et al., 2011; Rötter et al., 2012), especially for its ability to

162 work on a daily basis for simulating multi-crop scenarios, in addition to water-soil  
163 dynamics (Richard's equation for our case) and nitrogen budgets.

### 164 **2.2.2. Datasets for model calibration and evaluation**

#### 165 *Experimental datasets for winter wheat model calibration and evaluation*

166 Five winter wheat plots were selected within the region of mid-Bekaa, corresponding to  
167 two dominant soil types with different water holding capacities (low: 100-175 mm/m and  
168 high: 175-250 mm/m). Above ground biomass (AGB), dry matter production (DMP), soil  
169 water content (SWC), and above ground nitrogen (AGN) were measured at four  
170 physiological stages and replicated three times within each winter wheat plot (Table 1).

171

172

173 Above ground biomass (AGB) was measured by a destructive method. After weighing the  
174 fresh samples for each replication within each plot, the samples were cut up, mixed and  
175 quartered and a representative sample was oven dried at 70 °C until constant weight was  
176 reached (Catchpole and Wheeler, 1992).

177 Soil water content (SWC) was measured using the gravimetric method. For each of the  
178 three pedological horizons (the depth of each soil horizon varied among plots), a sample  
179 of soil was taken out, weight measured fresh, then sent to the oven to dry at 105 °C until  
180 constant weight was obtained. For each winter wheat reference plot, the measurement was  
181 replicated three times randomly at each depth at five crop development stages (Reynolds,  
182 1970).

183 Above ground nitrogen (AGN) was measured following the Kjeldahl N method (Rodriguez  
184 and Miller, 2000). Crop N uptake for each treatment was calculated based on the  
185 corresponding data of dry matter production and N content for each treatment, at each  
186 sampling date. Winter wheat in-situ measurements are summarized in table 2. It shows the  
187 minimum, maximum and average results of the measurements of replications. SWC  
188 measurements in the different horizons were also considered.

189

190

### 191 *Survey datasets for potato and fava bean model calibration and evaluation*

192 A survey was conducted in the study site inquiring about potato and fava bean crops (four  
193 farmers of each crop type), including sowing and harvesting dates, management practices  
194 and yields. Table 3 includes the characteristics of potato and fava bean plots, to which data  
195 on sowing and harvesting dates, management practices and yields correspond.

196

197

198 Weather data (daily data on precipitation, maximum air temperature, minimum air  
199 temperature and incoming solar radiation from 1997 to 2017) were collected from a station  
200 located in the study area (Zahle).

201

### 202 **2.2.3. Model calibration and evaluation process**

203 Following Belhouchette et al. (2008), only the two most sensitive parameters were  
204 calibrated for simulation with CropSyst, namely: the above ground biomass transpiration  
205 coefficient ( $AGB_T$ ) and the conversion of light to above ground biomass coefficient

206 ( $AGB_{IPAR}$ ). These parameters were derived manually by changing the crop parameters until  
 207 a satisfactory agreement between the predicted and simulated yield and biomass was  
 208 achieved (Singh et al., 2008). While for potato and fava bean crops, the calibration was  
 209 based on yields reported through the questionnaire conducted, as suggested by Komarek et  
 210 al. (2017).

211 CropSyst was validated by comparing the simulated and measured values of the observed  
 212 plots used for validation (section 2.2.2, Tables 1, 2 and 3), which were not part of the  
 213 calibration process (one plot of each crop was used for calibration, while the others were  
 214 used for validation). In the case of wheat, these values correspond to AGB, AGN, and SWC  
 215 over the whole growing cycle, while for potato and fava bean crops, according Komarek  
 216 et al. (2017), only the yield was validated after calibration. Root Mean Square Error  
 217 (RMSE) was used to calculate the error of estimates as:

$$218 \quad RMSE = [Np^{-1} \sum_{i=1}^N (P_i - O_i)^2]^{0.5} \quad (3)$$

219 where  $Np$  is the number of pairs of observed ( $O_i$ ) and simulated ( $P_i$ ) data.

220 Then, the RMSE was computed relative to the mean of the observed values ( $\bar{O}$ ) as:

$$221 \quad RRMSE = \frac{RMSE}{\bar{O}} \quad (4)$$

222 To have proper insight on the model efficiency, the model efficiency “EF” indicator was  
 223 calculated as:

$$224 \quad EF = 1 - \frac{\sum_{i=1}^N (P_i - O_i)^2}{\sum_{i=1}^N (O_i - \bar{O})^2} \quad (5)$$

225 The model efficiency indicator varies from  $-\infty$  to  $+1$ . Negative values can indicate bias in  
226 linear models, yet could not be the case in non-linear models.

227 As an indicator to estimate correlation/regression, index of agreement “d” was calculated  
228 as:

$$229 \quad d = 1 - \frac{\sum_{i=1}^N (P_i - O_i)^2}{\sum_{i=1}^N (|P_i - \bar{O}| + |O_i - \bar{O}|)^2} \quad (6)$$

230 where  $O_i$  represents the observed data,  $P_i$  represents the predicted data and  $\bar{O}$  is the average  
231 of the observed data. The Willmott index of agreement (d) varies from 0.0 (poor model) to  
232 1.0 (perfect model), similar to the interpretation of the coefficient of determination ( $R^2$ ).

233 Eqs. 3, 4, 5 and 6 were applied to the validation plots within the region (four winter wheat  
234 plots, three potato plots, and three fava bean plots), to make sure that by changing the  
235 management practices and initial conditions, the model kept on generating satisfactory  
236 estimates.

237

### 238 **2.3. Developing the scenarios to be simulated by the CropSyst model**

239 In this study, different wheat-based cropping systems of different rotation types (wheat-  
240 wheat, wheat-fallow, wheat-potato, and wheat-fava bean, see Table 3) in two soil water  
241 holding capacity (WHC) types, are simulated. The two soil types consist of different  
242 horizons of different depth. Table 4 illustrates the soil characteristics of each soil type.  
243 Each soil type is not uniform in terms of depth, rather consists of separate soil horizons.

244

245

246 We note hereby that full fertilization (Nitrogen) and full irrigation (water) follow the  
247 amounts applied on the plot used for calibration (Plot ID 1 in Table 1), using the fixed  
248 fertilization and fixed irrigation at fixed dates in CropSyst model. Four types of wheat  
249 management systems were considered:

250 F1-I1: Full fertilization (230 kgN ha<sup>-1</sup>) and full irrigation (100 mm)

251 F1-I0: Full fertilization (230 kgN ha<sup>-1</sup>) and no irrigation.

252 F0-I1: No fertilization and full irrigation (100 mm).

253 F0-I0: No fertilization and no irrigation.

254 Thus, it is noted that during the simulations, these different management practices are only  
255 applied in the case of wheat, while the management of potato and fava bean crops does not  
256 change (management of Potato 1 and Fava bean 1 in Table 3 are used for simulation). As  
257 shown by El Khansa (2017), potato farmers do not alter their water and fertilizer inputs as  
258 they know in advance the high risk this involves. In the case of fava beans, the management  
259 is fixed, a small amount of nitrogen is the only input they apply, if any.

260 Each cropping system scenario is run from 1997 to 2017. The output of each scenario  
261 (cropping system) is 20 simulated years composed of 10 rotations (each lasts 2 years).  
262 Table 5 summarizes the scenarios simulated. We note that the irrigation was simulated in  
263 CropSyst using a fixed amount of water in a fixed time, as expressed by the farmers during  
264 our survey.

265

266

267        **2.4. Calculation of the productivity and efficiency indicators for assessing the**  
268                **performance of wheat-based cropping systems**

269        *Calculation of the productivity indicators*

270        - The net profit (US\$ ha<sup>-1</sup>) indicator: computed at rotational level (2 years) as follows:

271         $NP_r = Rev_r - Cost_r$  (7)

272        Where *NP* stands for net profit at rotational level (*r*), *Rev* stands for revenue per rotation  
273        (*r*) and *Cost* stands for the variable production cost of each rotation (*r*). We note hereby  
274        that the variable production cost (*Cost*) represents all the costs needed to establish a  
275        particular rotation. As the total simulation period is 20 years, the net profit is calculated 10  
276        times for each cropping system.

277        In order to calculate the *Rev<sub>r</sub>* and the *Cost<sub>r</sub>* (Eq. 7) of each of the cropping systems, data on  
278        input costs and output prices were collected through a local survey conducted at the study  
279        site (Table 6), since in Lebanon, there is a lack of national official statistical sources for  
280        annual input and output costs and prices. The input costs collected correspond to costs  
281        related to cultivation (wheat, potato or fava bean), while output prices refer to selling the  
282        produce (i.e. wheat grain yield, straw yield, potatoes, and fava bean grains). The input costs  
283        and output prices collected through our survey correspond to an average of 5 years as the  
284        prices are more or less stable and do not witness dramatic fluctuations. This also appears  
285        when comparing to FAOSTAT (<http://www.fao.org/faostat/>) data. Regarding the  
286        respondents, costs related to wheat were asked from 10 wheat farmers, costs related to  
287        potato were asked from 10 potato farmers and costs related to fava bean were asked from  
288        6 fava bean farmers. The farmers were selected randomly, yet we intended to interview

289 those who have been exercising the cultivation for a relatively long period (minimum 10  
290 years). In addition, we aimed asking farmers who own their lands. The responses collected  
291 from these farmers (Table 6) were homogeneous by looking at the averages and the  
292 standard deviations.

293 It is noted that the input costs for both potato and fava bean crops are the variable  
294 production costs including costs of fertilizer, water seeds, and labour. As simulating  
295 different management systems is only carried out in the case of wheat, the variable  
296 production cost (the only cost considered) to establish potato or fava bean cultivation is  
297 equal to the input cost (Table 6) and does not change with the different scenarios.

298

299

300 - The average protein production ( $\text{kg ha}^{-1}$ ) indicator is computed at rotational level  
301 following two equations (Eqs. 8 & 9) for each cropping system. The purpose of this is to  
302 serve comparing rotations of different crops within, to eventually come up with conclusions  
303 on the protein production of each rotation.

304 First, the protein production ( $\text{kg ha}^{-1}$ ) for each rotation is computed by considering the final  
305 yield of each crop within the rotation and its corresponding protein percentage:

$$306 \quad P_r = [Yield_{Crop1} \times \%P_{Crop1}] + [Yield_{Crop2} \times \%P_{Crop2}] \quad (8)$$

307 where  $P_r$  is the amount of protein ( $\text{kg ha}^{-1}$ ) produced by each rotation (r) (2years),  $Yield_{Crop1}$   
308 is the yield ( $\text{kg ha}^{-1}$ ) of the first crop within the rotation,  $Yield_{Crop2}$  is the yield ( $\text{kg ha}^{-1}$ ) of  
309 the second crop within the rotation,  $\%P_{Crop1}$  is the percentage of protein contained in 1 kg

310 of the yield of crop1 and  $\%P_{Crop2}$  is the percentage of protein contained in 1 kg of the yield  
311 of crop2. Equation 8 is applied 10 times for each cropping system.

312  $Yield_{Crop1}$  and  $Yield_{Crop2}$  are obtained from the CropSyst outputs. As for  $\%P_{Crop1}$  and  
313  $\%P_{Crop2}$ , according to the USDA reports (USDA, 2018), 1 kg of grain contains 124.2 g of  
314 protein, 1 kg of potato tuber<sub>r</sub> contains 25.7 g of protein and 1 kg of fava bean<sub>r</sub> contains  
315 261.2 g of protein.

316 Then, the accumulated protein amounts of the 10 rotations ( $Nr$ ) within each cropping  
317 system are added up. Eventually, the average is measured by dividing the product by the  
318 total number of rotations within each cropping system:

$$319 \quad \bar{P}_r = \frac{\sum_{r=1}^{Nr} (P_r)}{Nr} \quad (9)$$

320 where  $\bar{P}_r$  is the average protein production ( $\text{kg ha}^{-1}$ ) at rotational level.  $r$  is the rotation.  $Nr$   
321 is the total number of rotations (=10 in this study).

### 322 ***Calculation of the efficiency indicators***

323 The nitrogen-use efficiency ( $NUE$ ) (Darwish et al., 2006a; Gaudin et al., 2015;  
324 Rahimizadeh et al., 2010) and water-use efficiency ( $WUE$ ) (Kang et al., 2002; Sadras,  
325 2004) for the average 10-year wheat crop presented in each of the cropping systems  
326 (rotation type and wheat management) are computed following two equations (Eqs. 10 &  
327 11).

$$328 \quad NUE_{Wheat} = \frac{AGN_1}{(N_{Supply1} + TSM)} \quad (10)$$

$$329 \quad WUE_{Wheat} = \frac{GY}{ET_{Actual}} \quad (11)$$

330 where  $NUE_{wheat}$  is the nitrogen-use efficiency calculated for the 10-years (out of a total of  
 331 20 years) of the wheat crop.  $AGN_I$  ( $\text{kgN ha}^{-1}$ ) stands for above ground nitrogen when wheat  
 332 is fertilized.  $N_{SupplyI}$  corresponds to the amount of supplied N fertilizer ( $\text{kgN ha}^{-1}$ ), when  
 333 applied.  $TSM$  corresponds to total soil mineralization rate accounting for N soil pool ( $\text{kgN}$   
 334  $\text{ha}^{-1}$ ).  $WUE_{wheat}$  is the water-use efficiency calculated for the 10years (out of a total of 20  
 335 years) of wheat cultivation.  $GY$  corresponds to grain yield.  $ET_{Actual}$  stands for  
 336 evapotranspiration (mm).

337 Then, the apparent recovery efficiency by difference ( $ARED$ ) is compared following  
 338 equations 12 & 13, to capture the added value of supplied N fertilizers and irrigation to  
 339 wheat within the different cropping systems.

$$340 \quad ARED_N = \frac{AGN_1 - AGN_0}{N_{Supply1} - N_{Supply0}} \quad (12)$$

$$341 \quad ARED_W = \frac{GY_1 - GY_0}{W_{Supply1} - W_{Supply0}} \quad (13)$$

342 where  $ARED_N$  and  $ARED_W$  correspond to apparent recovery efficiency by difference, for  
 343 nitrogen and water respectively.  $N_{Supply0}$  corresponds to the amount of supplied N fertilizer  
 344 ( $\text{kgN ha}^{-1}$ ), when not supplied, which is equal to zero.  $AGN_0$  ( $\text{kgN ha}^{-1}$ ) corresponds to the  
 345 above ground N when wheat is never fertilized.  $GY_I$  ( $\text{kg ha}^{-1}$ ) and  $GY_0$  ( $\text{kg ha}^{-1}$ ) stand for  
 346 grain yield under full irrigation and no irrigation at all, respectively.  $W_{SupplyI}$  stands for the  
 347 amount of water supplied as irrigation (mm).  $W_{Supply0}$  is the amount of water supplied as  
 348 irrigation (mm), when not supplied, which is equal to zero.

## 349 **2.5. Calculation of the “economic risk of low relative productivity”**

350 Taking into account that in the area (MENA region and many developing countries), access  
351 to banks' credits or other credit institutions has hardly been established or has fallen in  
352 disorder (Asseldonk et al., 2013), the risk calculation considered in this study is in line with  
353 the farmers' concerns of being financially secured to keep on sustaining their cropping  
354 system with no or low financial failure by mobilizing their net profit to invest in the rotation  
355 that follows by covering its variable production cost. The financial failure considered here  
356 is not being able to re-establish their rotations for preserving their livelihoods. In practice,  
357 this is seen when the net profit of a particular rotation in year 1 is less than the variable cost  
358 of the same rotation in year 2, meaning that the farmer who wishes to re-cultivate this  
359 particular system, must mobilize external resources to increase the difference between the  
360 net profit and the variable production cost. The risk calculation proposed is an original  
361 procedure different from the standard calculations within the literature. The variation in the  
362 risk in this study is basically related to yield variations as prices in the area are seen more  
363 or less stable over the last years. In addition, it is important to mention that the risk  
364 considered in this study is to compare different cropping systems (scenarios). In other  
365 words, when the financial failure is seen, it does not mean that the farmer's livelihood is  
366 terminated, yet they witness a risk of not being able independently in re-cultivating the  
367 same system for the next rotation (two coming years), by covering its total production  
368 costs.

369 Concretely, the economic risk of low relative productivity, which is expressed as a score,  
370 is calculated as follows:

$$371 \text{Risk}_{CS} = (\sum_{r=1}^{Nr} W_r \times (+RD_r)) \times F_{r/Nr} \quad (14)$$

372 where  $Risk_{cs}$  is the economic risk score that will be assigned to each of the cropping  
373 systems, taking into account the 10 rotations within.  $r$  corresponds to the rotation.  $Nr$   
374 corresponds to the total number of rotations ( $Nr=10$ ).

375  $W_r$  is the normalized weight of the variable production cost at rotational level. As the tested  
376 rotations have different production costs (different crops and management systems), a  
377 normalized weight of the variable production cost is computed for each rotation, as a ratio  
378 of the production costs of different rotations to the production cost of the most expensive  
379 rotation (i.e. wheat-potato). Weight is calculated as follows:

$$380 \quad W_r = \frac{Cost_r}{Cost_{WP}} \quad (15)$$

381 where  $W_r$  is the weight of each rotation varying between 0 and 1,  $Cost_r$  is the full production  
382 cost of a rotation,  $Cost_{WP}$  corresponds to the full production cost of the wheat-potato  
383 rotation type.

384  $RD_r$  is the relative deviation of the net profit from the cost at each rotation. Given that the  
385 farmer will continue applying the same rotation type and wheat management system, the  
386 relative deviation of this net profit/rotation from the total cost needed to re-establish the  
387 same rotation (of the same rotation type and wheat management system) is computed as  
388 follows:

$$389 \quad RD_r = \frac{Cost_r - NP_r}{Cost_r} \quad (16)$$

390 where  $RD_r$  is the relative deviation of the net profit from the cost for each rotation within  
391 each cropping system,  $Cost_r$  is the variable production cost of a particular rotation (e.g.  
392 wheat-wheat in F1-I1 management system) and  $NP_r$  is the net profit of this particular

393 rotation within a particular cropping system. It is noted that within the whole period (20  
394 years) of simulation in a particular cropping system (10 rotations), the  $Cost_r$  is fixed and  
395 doesn't change, while the  $NP_r$  changes for every rotation (2 years). If the output of  $RD_r$  is  
396 negative, meaning that the  $NP_r$  is higher than the  $Cost_r$ , then the corresponding rotation is  
397 neglected and is not considered when applying Eq. 14.

398  $F_{r/Nr}$  is the frequency of rotations (ratio from 0 to 1) whose net profit is lower than the  
399 variable production cost, out of the 10 rotations ( $Nr$ ). To highlight the repetition of rotations  
400 with a deficit (positive  $RD_r$ ), i.e. in which the net profit is lower than the cost, the ratio of  
401 the occurrence of this "bad" event from the whole number of rotations ( $Nr=10$ ) is computed  
402 as follows:

$$403 \quad F_{r/Nr} = \frac{\#PositiveRD_r}{Nr} \quad (17)$$

404 where  $\#PositiveRD_r$  is the number of rotations within a cropping system whose  $RD_r$  is  
405 positive ( $NP_r < Cost_r$ ). Eq. 17 is applied for each of the 16 cropping systems, in both low  
406 and high WHC soils.

407

## 408 **3. Results**

### 409 **3.1. Calibration and validation of the CropSyst model**

410 The results of the validation of the CropSyst model are therefore generated after the  
411 calibration. Following the rating proposed by Jamieson et al. (1991), the RRMSE ranged  
412 between 9.2% and 12.7%, it can thus be considered as good to excellent simulation of dry  
413 matter production (DMP). For above ground nitrogen (AGN) simulation, RRMSE ranged

414 from 7.7% to 25.0% and can be considered as average to good. In the case of the average  
415 soil water content (SWC) simulation, RRMSE ranged from 21.0% to 34.3%. As regarding  
416 the efficiency indicator (EF), for the DMP, the values ranged between 0.946 and 0.99,  
417 between 0.9 and 0.99 for AGN and between -5.5 and -0.57 for SWC. Concerning the index  
418 of agreement (the correlation/regression indicator), the values ranged between 0.990 and  
419 0.996 for the DMP, between 0.96 and 0.997. As for the SWC, the index of agreement  
420 produced values between 0.53 and 0.64. Hence, the calibrated model can be counted as  
421 satisfactory in terms of simulating yield, water, and nitrogen cycles.

### 422 **3.2. Wheat grain yield as altered by the effects of rotation, management system,** 423 **and soil type**

424 The effects of different management systems, soil WHC, and rotations on wheat grain  
425 yields ( $\text{kg ha}^{-1}$ ) are compared for the different wheat-based systems, as shown in Table 7.  
426 Before applying the mean separation test, we checked for homogeneity (using Chi-square  
427 test) and normality (using Shapiro Wilk's W test) assumptions. For all our cases, the null  
428 hypothesis was rejected by the Chi-square test confirming that the rotation types are linked  
429 to the wheat grain yield (significant results) and non-significant for the Shapiro-Wilk's W  
430 test, thus the normality assumption was checked. Tuckey test (2-way ANOVA analysis)  
431 was used to its ability in reducing type 1 and 3 errors (Acutis et al., 2012)

432

433

434 In low WHC soil, wheat grain yields produced by a wheat-potato rotation were the highest  
435 (with no clear effect of the rotation type). However, in all rotations, wheat grain yields

436 significantly decrease as the input amounts (fertilization and irrigation) decrease or are not  
437 applied (e.g. in the case of a wheat-potato rotation it drops from 4515 kg ha<sup>-1</sup> in F1-I1 to  
438 3433 kg ha<sup>-1</sup> in F0-I0).

439 When wheat is fertilized with no irrigation (F1-I0), wheat grain yields in a wheat-wheat  
440 rotation (3787 kg ha<sup>-1</sup>) are similar to those observed in a wheat-potato rotation (3757 kg  
441 ha<sup>-1</sup>), meaning that water stress in such a soil type (low WHC) is more significant than  
442 nitrogen stress. This finding agrees with the results reported earlier (Huang et al., 2003).

443 When wheat is not fertilized (irrigated or not), wheat grain yields in wheat-fallow and  
444 wheat-fava bean rotations are higher than those observed in a wheat-wheat rotation (e.g.  
445 3873 kg ha<sup>-1</sup> in a wheat-fava bean rotation versus 3447 kg ha<sup>-1</sup> in a wheat-wheat rotation)  
446 and similar to those observed in a wheat-potato rotation (3280 kg ha<sup>-1</sup> in a wheat-fava bean  
447 rotation versus 3433 kg ha<sup>-1</sup> in a wheat-potato rotation). This means, indeed, that fallow  
448 and fava bean when in rotation with wheat better mitigate water and nitrogen stresses on  
449 wheat grain yields, in comparison with wheat-wheat rotation. This result is in agreement  
450 with other findings (López-Bellido et al., 2012).

451 In high WHC soil, when wheat is fertilized (F1-I1 and F1-I0), there is no significant effect  
452 of the rotation type on the wheat grain yield production. This is primarily attributed to the  
453 type of soil (high WHC) that can hold more green water than low WHC. Hence, the loss in  
454 yield that appeared in all the rotations from irrigated to rain-fed in high WHC (I1 to I0) is  
455 due to water stress. Similar results were reported in the region (Sohi et al., 2009). However,  
456 this loss is not as prominent as the one seen in low WHC soil (11% versus 18% of wheat  
457 grain yield drop).

458 However, when nitrogen is limited (F0-I1 and F0-I0), as was reported for the soils of the  
459 NENA region (Darwish et al., 2018), the wheat-wheat rotation always leads to significantly  
460 lower wheat grain yields ( $4665 \text{ kg ha}^{-1}$ ) than the other tested rotation types (over  $5200 \text{ kg}$   
461  $\text{ha}^{-1}$ ). This is because wheat-fallow and wheat-fava bean rotations are less intensive in  
462 terms of nitrogen demand, and do not neglect the nitrogen fixation ability of legumes  
463 (Constantin et al., 2010; Moreau et al., 2012), as well as the fertilization of potatoes in the  
464 wheat-potato rotation. This means that nitrogen and water stresses are higher in the case of  
465 a wheat-wheat rotation when compared with other rotations.

466 Nevertheless, still in high WHC soils, wheat-wheat is the only rotation in which wheat  
467 grain yields did drop significantly when changing from a wheat intensive management  
468 system (F1-I1) ( $6083 \text{ kg ha}^{-1}$ ) to wheat semi-intensive management systems (F1-I0 and F0-  
469 I1) ( $5250 \text{ kg ha}^{-1}$  and  $5126 \text{ kg ha}^{-1}$ , respectively), as well as when both nitrogen and water  
470 were ceased (F0-I0) ( $4665 \text{ kg ha}^{-1}$ ). This suggests that avoiding wheat intensive  
471 management systems (when in rotation with fallow, potato and fava bean) would not cause  
472 water nor nitrogen stress, preserving the level of wheat grain yields.

### 473 **3.3. Nitrogen and water Apparent Recovery Efficiency by Difference (ARED)**

474 To grasp the added value of input resources (water and nitrogen) on wheat grain yields, the  
475 Apparent Recovery Efficiency by Difference (ARED) for the two input resources (Keller  
476 and Keller, 1995; Rao et al., 1992) is calculated, for wheat grain yields following different  
477 previous crops (wheat, fallow, potato and fava bean) in the two soil water holding  
478 capacities (low and high) [Eqs. (12) & (13) section 2.4.1]. ARED was computed for  
479 nitrogen in both cases of irrigation (I1 and I0), as well as for irrigation in both cases of

480 nitrogen supply (F1 and F0) (Fig. 2). The separation of means was done using 2-way  
481 ANOVA analysis (Tukey test).

482 Concerning fertilization, wheat grain yields increased the most because of nitrogen  
483 fertilization ( $\text{ARED}_N$ ) when cultivated in a wheat-wheat rotation, whether irrigated or not,  
484 in low WHC soil (Fig. 2i & 2iii) (4.61 and 2.79, respectively) or in high WHC (Fig. 2ii &  
485 2iv) (4.3 and 2.46, respectively). This means that for each 1 kg of added N, the increase in  
486 grain yields for wheat in the wheat-wheat rotation is greater than that observed in other  
487 rotations. In other words, wheat grain yields in a wheat-wheat rotation will be more  
488 sensitive to lower fertilization, and thus more likely to decrease than wheat grain yields in  
489 other rotations. The lowest slope observed for wheat grain yields was in the case of a wheat-  
490 fava bean rotation, conforming to several studies that show that fava bean is an excellent  
491 previous crop (Angus et al., 2015; Plaza-Bonilla et al., 2017; Yau et al., 2003), which partly  
492 reduces the dependence of the main crop (winter wheat in this case) on nitrogen fertilization  
493 (Voisin et al., 2013).

494 In the case of wheat-fallow and wheat-potato rotations, the results were more nuanced. In  
495 low WHC soil, fallow land allows for a better use of N than potato as a previous crop, as  
496 soil nutrients are rebalanced and soil biota is re-established (Plaza-Bonilla et al., 2017). On  
497 the other hand, potato becomes a better previous crop than fallow land in high WHC soils.  
498 This is due to the ability of these soils to store more water and facilitate the flux of nitrogen  
499 to the roots by mass flow, for the next crop.

500 Concerning irrigation, the results are quite surprising as in low WHC (Fig. 2v), wheat in a  
501 wheat-wheat rotation requires less water (in terms of irrigation) than in other rotations,  
502 which contradicts other studies that show that wheat is more sensitive to irrigation (thus

503 more dependent) in a wheat-wheat rotation type (Gu et al., 2002; Musick et al., 1994;  
504 Zhang and Oweis, 1999). This result can be explained by larger periods of fallow land than  
505 in the case of wheat-wheat rotations (maximum of 3 months of fallow). Therefore leading  
506 to larger amounts of evaporated water. This evaporated water, however, becomes less  
507 important in high WHC (Fig. 2vi), in which more water is stored to its high capacity. In  
508 coherence with the literature (Passioura and Angus, 2010), well-fertilized wheat (F1)  
509 becomes more water reactive in a wheat-wheat rotation than other rotations. On the other  
510 hand, wheat in a wheat-fava bean rotation becomes more reactive to water if nitrogen is  
511 not applied. These results are consistent with multiple published studies, which state that  
512 legumes are excellent previous crops, especially in a poorly fertilized system.

#### 513 **3.4. Trends of the crops' yields (10 rotations) over the simulation period**

514 Out of the period of 20-years of simulation, 10 particular years (1998, 2000, 2002, 2004,  
515 2006, 2008, 2010, 2012, 2014 and 2016) witnessed the cultivation of each of the three  
516 crops (wheat, potato and fava beans). In Figure 3 below, the trends of each of the three  
517 crops is represented, for both water holding capacity soils (WHC). In each year, four  
518 agricultural practices were simulated (Table 5). Thus, as we aim to show the general trend,  
519 the values of the four outputs of the four agricultural practices simulated were averaged.

520 The average wheat grain yield trend shows a slight increase until the 6<sup>th</sup> rotation (1998 till  
521 2008), then a sharp drop until the 8<sup>th</sup> rotation (2012) then an increase afterwards. Similar  
522 to the trend of winter wheat, the yield of fava beans increased from the 1<sup>st</sup> rotation till the  
523 2<sup>nd</sup> one, then slight increase till the 6<sup>th</sup> rotation before the sharp drop till the 8<sup>th</sup> rotation  
524 (2012). An increase was seen afterwards till the 9<sup>th</sup> rotation before finally a decrease at the  
525 10<sup>th</sup> one. As for potato, the trend was more or less stable with a slight decrease until the 7<sup>th</sup>

526 rotation, continues decrease was seen till the 8<sup>th</sup> rotation before a sharp increase at the 9<sup>th</sup>  
527 and 10<sup>th</sup> rotation.

### 528 **3.5. Rotation performance (productivity and efficiency) and economic risk of low** 529 **relative productivity**

530 Productivity (protein and net profit) at rotational level [Eqs. (7) & (9) section 2.4.1] versus  
531 the resource-use efficiency calculated for wheat crops [Eqs. (10) & (11) section 2.4.1], in  
532 each of the cropping systems are demonstrated (Fig. 4) for both soil types (low and high  
533 WHC). In addition, based on the economic risk score calculated following Eq. 14 (section  
534 2.4.2), the risk level of each of the cropping system is expressed.

535

536 Looking at the NUE (Fig. 4a & 3c), it is clear that for all systems efficiency decreases  
537 dramatically when nitrogen is applied. With respect to protein production (Fig. 4a),  
538 regardless of the management type, wheat-wheat (systems 1, 5, 9 and 13) and wheat-fava  
539 bean (systems 4, 8, 12 and 16) rotations produce the highest amounts of protein (between  
540 0.75 and 1.1 t rotation<sup>-1</sup> per ha followed by wheat-potato rotations (systems 3, 7, 11 and  
541 15) that produce lower amounts depending on the management type (between 0.7 and 0.9  
542 t rotation<sup>-1</sup> per ha). Wheat-fallow rotations (systems 2, 6, 10 and 14) produce the least  
543 amount of protein (between 0.3 and 0.55 t rotation<sup>-1</sup> per ha). These results show that most  
544 cropping systems, when grown in low WHC soil in such semi-arid areas, are over-  
545 fertilized, which is relatively consistent with previous studies (Asseng et al., 2001; Ben  
546 Zekri et al., 2018; Garabet et al., 1998). Residual soil nitrogen can be subject to nitrification  
547 in well aerated loamy soils and nitrates can be leached and pollute the groundwater  
548 (Darwish et al., 2003).

549 Regarding the net profit (Fig. 4c), it is obvious from the results that the wheat-potato  
550 rotation is the most profitable rotation among the different rotations (from 8500  
551 US\$/rotation/ha to 8700 US\$ rotation<sup>-1</sup> per ha). Wheat-fava bean (around 2000 US\$  
552 rotation<sup>-1</sup> per ha) and wheat-wheat (around 1300 US\$ rotation<sup>-1</sup> per ha) rotations follow.  
553 Eventually, wheat-fallow is the least profitable in terms of net profit (around 660 US\$  
554 rotation<sup>-1</sup> per ha). This also confirms, therefore, that the cropping systems within the area  
555 are over-fertilized since efficiency decreases while the net profit does not witness a similar  
556 increase when intensifying the management system. In the long term, these practices may  
557 affect soil-ecosystem functions.

558 The wheat-potato rotation is the riskiest one, compared to other rotations. In addition, the  
559 wheat-fava bean rotation is not just more profitable than the wheat-wheat rotation, it is also  
560 economically much less risky. Thus, growing legumes in rotation with wheat reduces  
561 economic risk, as well as water and nitrogen dependence, compared to other rotations.  
562 Similarly, and on a more general basis, in low WHC soil types, the more intensive the  
563 systems, the riskier (economically) they are. This result contradicts several other studies  
564 that suggest intensification, as a factor, to increase production stability (Gaudin et al., 2015;  
565 Hartmann et al., 2015). This result shows that by intensifying the system in low WHC, that  
566 is to say dry-land soils that are poor in terms of physical and biological properties,  
567 productivity remains, efficiency decreases and economic and environmental sustainability  
568 decrease.

569 By looking at the WUE, intensive systems (except wheat-fallow rotations) are more  
570 efficient in terms of water-use than extensive systems. This result is consistent with the  
571 literature, which mentions that water is one of the most limiting factors in shallow soils of

572 arid areas (Sultana et al., 2009). Semi-intensive and extensive systems (systems 8, 9, 11,  
573 12, 13, 15 and 16) are then less efficient in terms of WUE. Wheat-fallow systems  
574 (especially the extensive ones: 10 and 14) are the least efficient in terms of water, basically  
575 due to large amounts of evaporated water.

576

577 By looking at the NUE (Fig. 5a & 5c), in high WHC soil, two groups of systems could be  
578 observed, belonging to fertilized (low NUE) and unfertilized systems (high NUE). Within  
579 the second group, wheat-fava bean (systems 4, 8, 12 and 16) and wheat-fallow (systems 2,  
580 6, 10 and 14) rotations are superior to wheat-wheat (systems 1, 5, 9 and 13) and wheat-  
581 potato (systems 3, 7, 11 and 15) rotations in terms of NUE. With respect to protein  
582 production (Fig. 5a), wheat-wheat and wheat-fava bean rotations were the best rotations  
583 compared to the other two rotations (1.2 to 1.5 t rotation<sup>-1</sup> per ha), followed by wheat-  
584 potato (1.1 t rotation<sup>-1</sup> per ha) and wheat-fallow (0.7 to 0.8 t rotation<sup>-1</sup> per ha) rotations.  
585 Results for soils with high WHC show that all rotations (except the wheat-wheat rotation)  
586 are over-fertilized. As for the net profit, regardless of the soil type and WHC, the wheat-  
587 potato rotation is the most profitable rotation (up to 12000 US\$ rotation<sup>-1</sup> per ha). Wheat-  
588 fava bean and wheat-wheat rotations follow (3500 US\$/rotation/ha and 2500  
589 US\$/rotation/ha, respectively). The wheat-fallow rotation comes last with around 1500  
590 US\$/rotation/ha.

591 Comparing the results of high WHC to those of low WHC soil types, wheat-wheat and  
592 wheat-potato rotations in high WHC soils become much less risky (if intensive  
593 management in terms of nitrogen is avoided) in terms of economic risk of low productivity.

594 Wheat-fallow and wheat-fava bean rotations, similarly to low WHC soils, are the least  
595 risky, economically, if adopted by farmers.

596 Regarding the WUE (Fig. 5b & 5d), the results show that water is not a limiting factor in  
597 high WHC soils (Zhang et al., 2008). Even though fertilized systems have shown slightly  
598 higher WUE than non-fertilized systems, the difference is not significant.

599

## 600 **4. Discussion**

601 When considering high resource-use efficiency, high system productivity (protein and  
602 profit) as well as low economic risk in terms of system sustainability as a whole package,  
603 it is clear that there is no comprehensible optimal scenario. Depending on our simulation  
604 results, the productivity (protein and net profit) of the different wheat-based cropping  
605 systems in two different soil WHC types, taking into consideration risk and wheat  
606 efficiency results, are plotted on a conceptual guide-map (Fig. 6). In addition, the  
607 productivity frontier is displayed to understand the best attainable scenarios.

608

609 Using this conceptual guide-map (Fig. 6) is essential for comparing the performance of the  
610 different wheat-based cropping systems, but also to identify the possible levers to improve  
611 the performance of these systems:

612 - Preserving deep soils for wheat cultivation: Such a strategy is achieved by combatting  
613 ongoing soil degradation, especially in dry and sub-dry areas. The presence of many typical  
614 cereal area plains in the Mediterranean region with low soil water holding capacity results  
615 in grain yield reduction due to post-anthesis terminal drought where a strong relationship

616 was found between actual evapotranspiration in the grain filling phase and the final grain  
617 yield. (Karrou and Oweis, 2012). As an example, the soil in the Medjerda-Tunisia (Souissi  
618 et al., 2017), Saïs-Morocco (Mohamed et al., 2018) and the Bekaa plain of Lebanon  
619 (Darwish et al., 2006b) typical cereal plains are more than 60% characterized by a low  
620 water holding capacity.

621 Deep soils in arid area are currently mostly dominated by cereal crops (especially durum  
622 and soft wheat), but a wide range of irrigated crops can also be observed, such as  
623 vegetables, orchards and fodder crops which represent at least 30% of the total cultivated  
624 area (Caiserman et al., 2019). These crops are less sensitive to the depth of the soil than  
625 cereal crops. Therefore, keeping deep soils for cereals could be a leverage for policy-  
626 makers in order to increase their production, input-use efficiency, and reduce the economic  
627 risk of low relative productivity by at least 48%, 35% and 38% respectively, as shown in  
628 this study.

629 - Reduction of the areas dedicated to wheat-fallow cropping systems (WF in Fig.5): such a  
630 cropping system is characterized by low economic and nutritional performances compared  
631 to other cropping systems. This explains why this system has gradually disappeared from  
632 arid areas, and only exists for those practicing multiple activities (MoA, 2010). For those  
633 farmers, the advantage of this system is that it requires very few inputs (particularly in high  
634 WHC soils) and especially involves very little risk compared to other cropping systems.  
635 Today, in the Mediterranean region, even if the areas dedicated to this type of rotation are  
636 less common than those dedicated to other rotation types, half of the land is left  
637 uncultivated each year (López-Bellido and López-Bellido, 2003). Most of the current  
638 intensification policies in dry areas encourage the mobilization of more inputs by totally or

639 partially subsidizing access to irrigation water, fertilizers, seeds, etc. By promoting wheat-  
640 based alternative systems other than wheat-fallow, it is potentially possible, according to  
641 our results, to increase rotational (2 year) protein production by at least 50%, at the Bekaa  
642 plain level.

643 - Intensification of wheat cultivation by increasing the amount of inputs: as expressed  
644 before, this lever is the most used by policy-makers and farmers to increase wheat  
645 production (Pala et al., 2007; Sadras, 2004). The guide-map (Fig. 6) shows that the  
646 intensification by increasing inputs is not effective in all cropping systems and the effects  
647 on rotational performance, efficiency and risk are not consistent with all cropping systems.  
648 Unfortunately, most farmers manage wheat cultivation regardless of the rotation type  
649 (Armengot et al., 2011), by considering intensified wheat management systems, presented  
650 in a wheat-wheat rotation as a reference pathway to increase productivity (Balkovič et al.,  
651 2014). Such means, which are encouraged by policy-makers, are not always reasonable as  
652 the efficiency of wheat in utilizing the resources decreases dramatically in different dry  
653 areas in the Mediterranean (Ben Zekri et al., 2018; Giménez et al., 2016; Ryan et al., 2007;  
654 Souissi et al., 2017; Yau et al., 2003).

655 - Switching from wheat-wheat rotation to wheat-legume crops (fava bean in our study):  
656 The wheat-legume rotation has shown better productivity than the wheat-wheat system,  
657 significantly higher efficiency (nitrogen and water) and much lower economic risk. Such  
658 findings were not very surprising as diversified rotations with catch crops usually yield  
659 high NUE (Beaudoin et al., 2005; Hansen et al., 2015; Moreau et al., 2012). Growing winter  
660 wheat with low inputs leads to a small sacrifice in terms of productivity, which may be a  
661 reason why farmers prefer intensified wheat-wheat cropping systems. Apart from

662 fertilization, mechanization limitations in legumes cultivation and the dependence on  
663 labour (weeding, harvesting) and establishments (e.g. storage warehouses), which would  
664 be pricey if not already owned by the farmer, are also obstacles preventing farmers from  
665 an easy switch to wheat-legume rotations. Moreover, fava beans production is a local  
666 product, which is sold locally and thus linked to the national level. This could be attributed  
667 to the low-trust that is given by farmers regarding national and local markets fearing  
668 “unlawful speculation”. Instead, many of them would prefer investing in wheat cultivation  
669 knowing in advance that the prices will not witness any change (even if negligible), as the  
670 government buys the grain yield.

671 Indeed, wheat farmers in Lebanon as well as in the MENA region do over-fertilize their  
672 crops for several reasons. First, farmers tend to believe that applying high rates of N would  
673 decrease their economic risk by increasing the grain weight and the final grain yield, and  
674 second because they do benefit from stable prices due to the support system at the national  
675 level. This issue (over-fertilization) has been widely reported in Tunisia (Cheikh M’hamed  
676 et al., 2014; Thabet et al., 2010), Egypt and Morocco (FAO, 2018). In another study, it was  
677 also reported that the over nitrogen fertilization all over the Mediterranean is highly  
678 impacting, negatively, the soil and water quality in the area in addition to reducing the  
679 economic yield (the huge N input represents 15% of the input cost in Morocco) (Heng et  
680 al., 2007). On the other hand, a study in Italy has suggested the increase of nitrogen  
681 application to up to 200 kg ha<sup>-1</sup> (similar to the rates applied in the Bekaa plain) for higher  
682 grain weight and better yield, taking into account the high environmental impacts (e.g.  
683 nitrogen leaching) (Abad et al., 2004).

## 684 **Conclusions**

685 Broadly, as frequently cited, increased production as well as increasing the efficiency in  
686 using the resources are the main requirements for feeding a vastly growing and changing  
687 world (Godfray et al., 2010). Many farmers, who work under small profit margins seek  
688 high production as a primary goal like many industrialized systems, which definitely trade  
689 off against ecosystem values and environmental aspects (Foley et al., 2005). Such an  
690 approach eventually leads to what we witness today in terms of negative environmental  
691 consequences and resource depletion (Pimentel, 2005), as well as negative social impacts  
692 (Marks et al., 2010). The results of our research showed that careful considerations should  
693 be coupled with recommending a specific cropping system, especially at field level. No  
694 optimal scenario was found (rotation and management) that may simultaneously guarantee  
695 low risk, significant protein production, large net profit, and high resource-use efficiency  
696 (NUE and WUE), at least for the rotations simulated in this study. Several studies have  
697 analyzed one crop (or one cropping system) in relation to its productivity and efficiency.  
698 Our results, nevertheless, by allowing the farmers and policy-makers to categorize existing  
699 systems in terms of their performance and risk, indicate that at field level, a wheat-legume  
700 rotation in which wheat is cultivated under semi-intensive and/or extensive agricultural  
701 management is very recommended, especially for those who cannot bear high-risk systems,  
702 securing both high efficiency in terms of resource-use and great protein production. In  
703 future research, anticipating our results, we intend to upgrade this study to the farm level,  
704 where more criteria and parameters may come across to propose a whole integrated system  
705 that is profitable, non-risky and sustainable, overpowering food security deterioration and  
706 nevertheless efficient in terms of resource-use efficiency.

707

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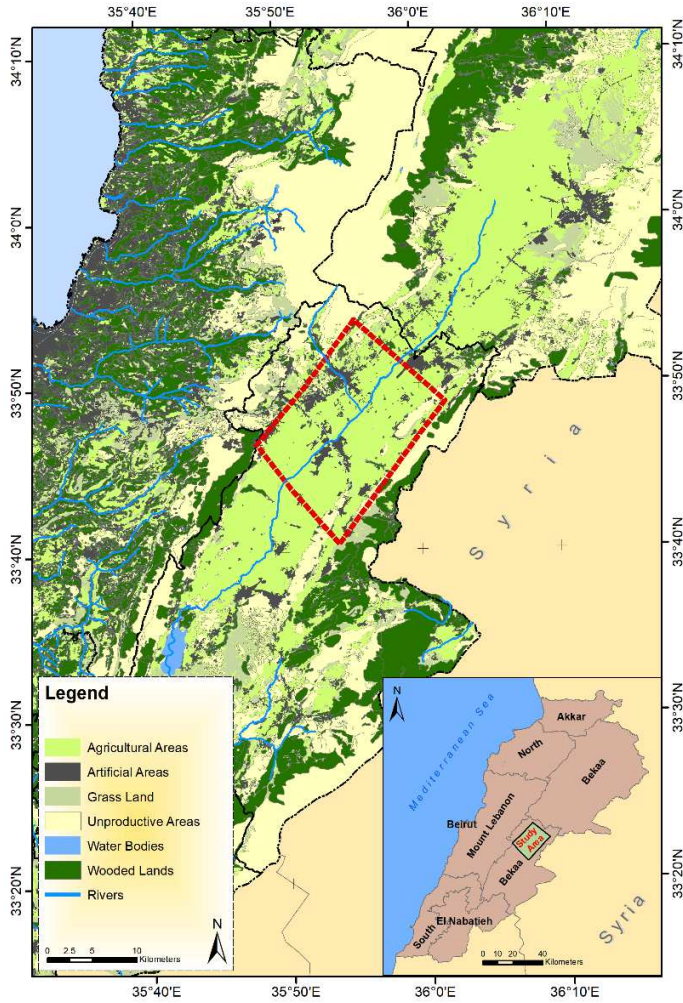
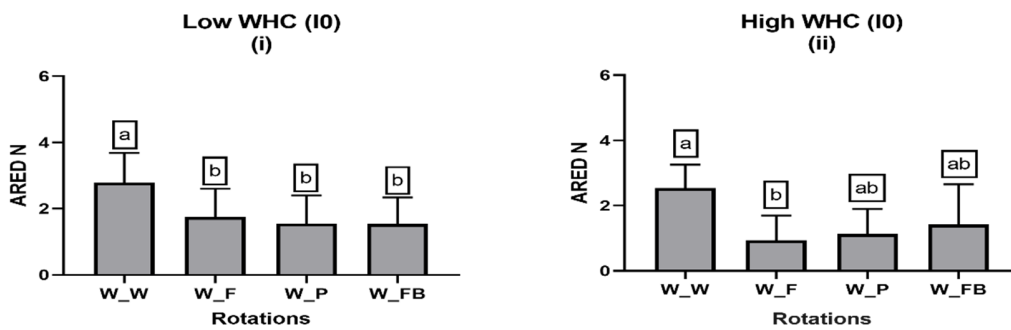


Fig. 1. Location of the Bekaa plain in Lebanon as well as the study area within the red tile



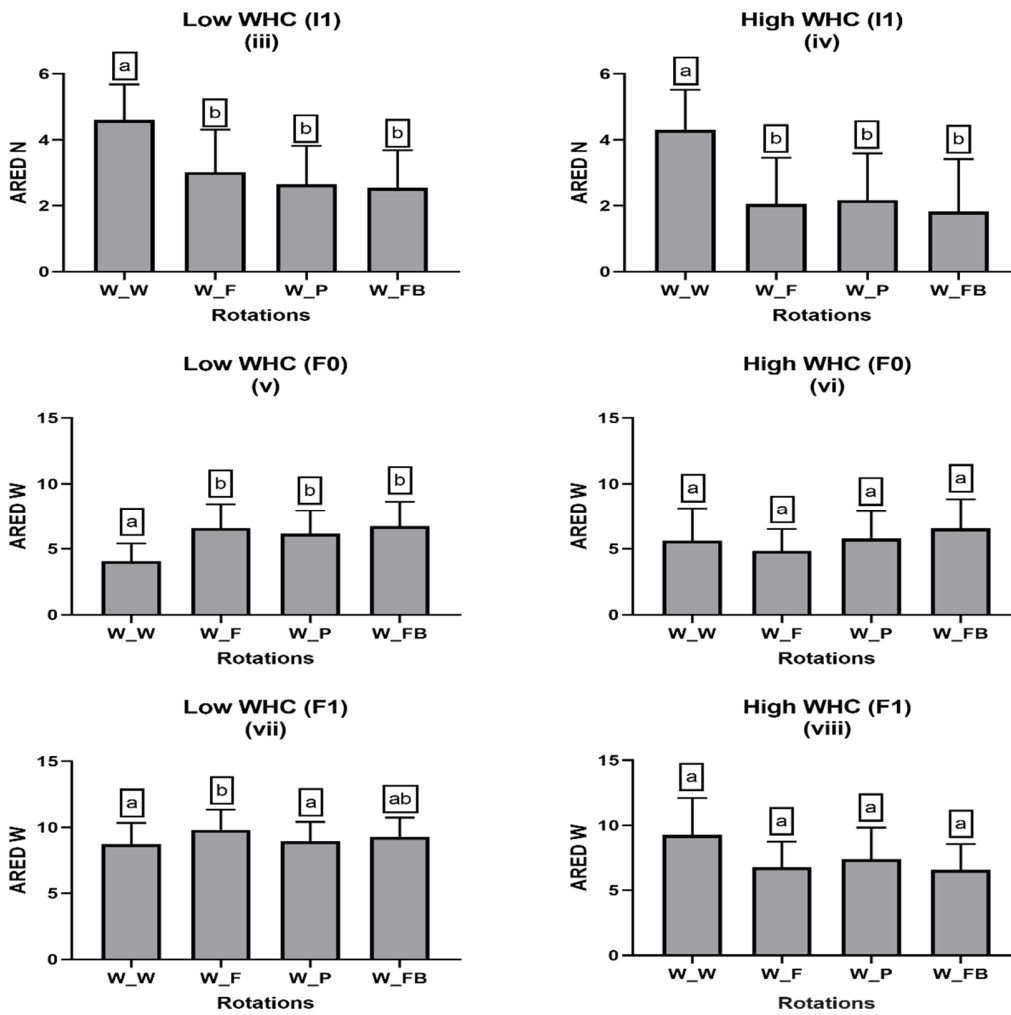
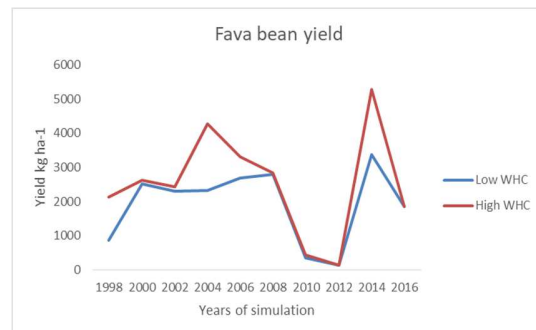
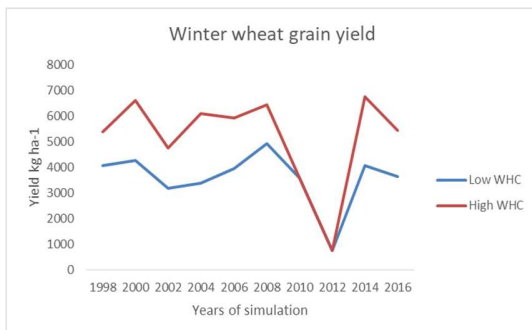


Figure 2. Apparent Recovery Efficiency by Difference (ARED) of nitrogen and irrigation of wheat crops, within each rotation, soil, and management type. a, b and c are symbols characterizing ARED which are significantly different or not regarding rotation.



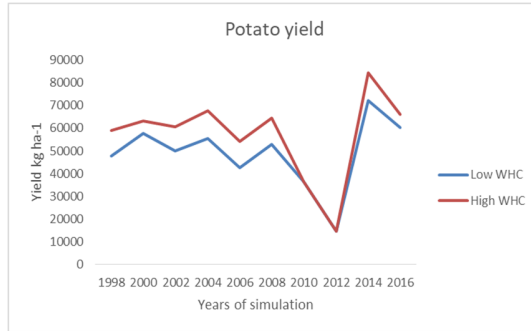


Figure 3. General yield ( $\text{kg ha}^{-1}$ ) trends of the three crops simulated over the 10 rotations in both WHC soils.

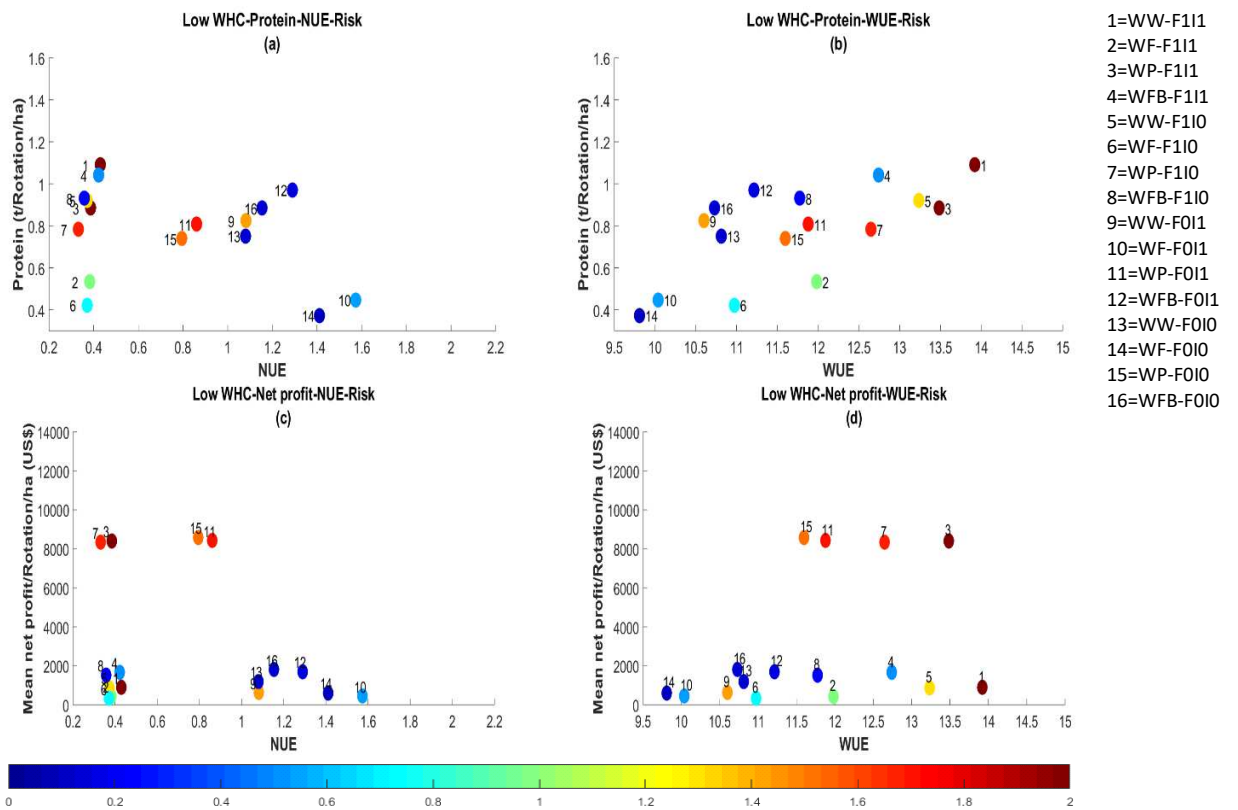


Figure 4. Risk representation of each of the cropping systems in low WHC soil denoted by the scale bar from dark blue (not risky at all) to dark red (very risky). The variation of protein production at rotational level versus wheat NUE (a) and wheat WUE (b), the variation of net profit at rotational level versus wheat NUE (c) and wheat WUE (d). A legend for each ID is presented to the right of the figure.

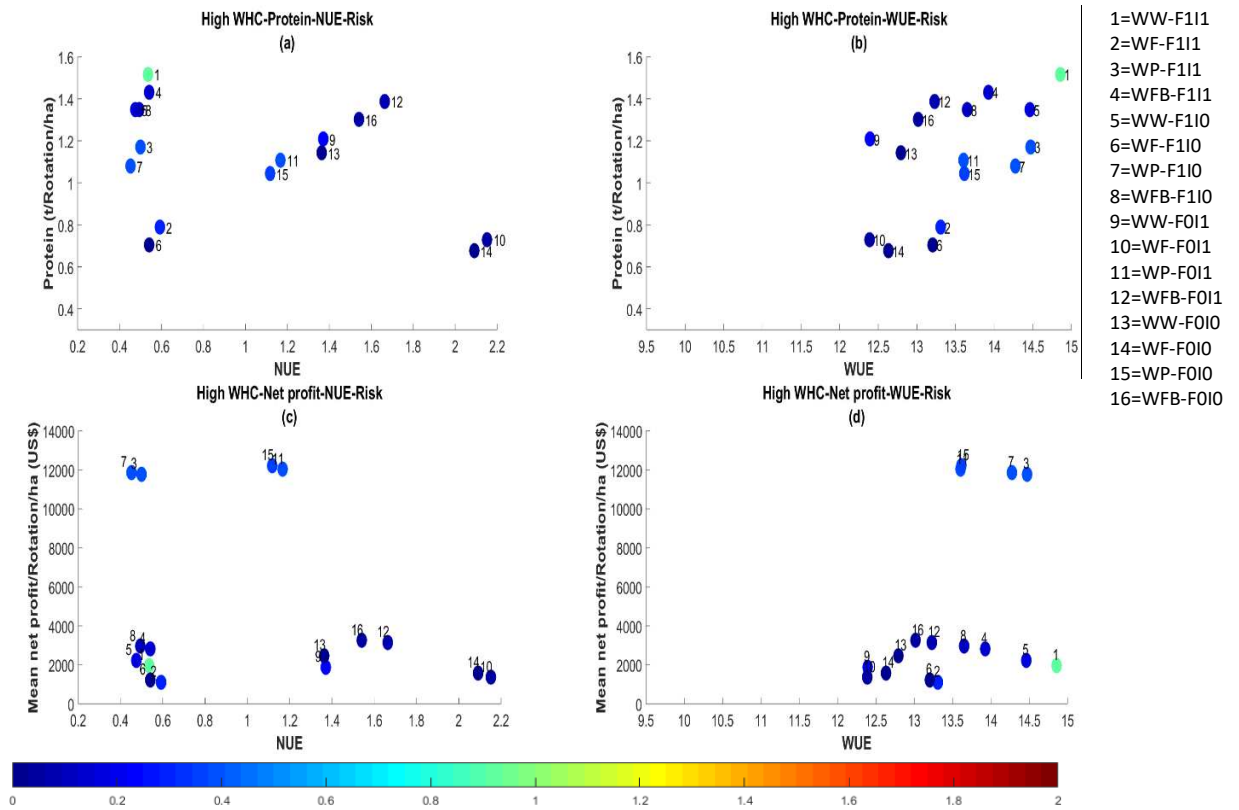


Figure 5. Risk representation of each of the cropping systems in high WHC soil denoted by the scale bar from dark blue (not risky at all) to dark red (very risky). The variation of protein production at rotational level versus wheat NUE (a) and wheat WUE (b), the variation of net profit at rotational level versus wheat NUE (c) and wheat WUE (d). A legend for each ID is presented to the right of the figure.

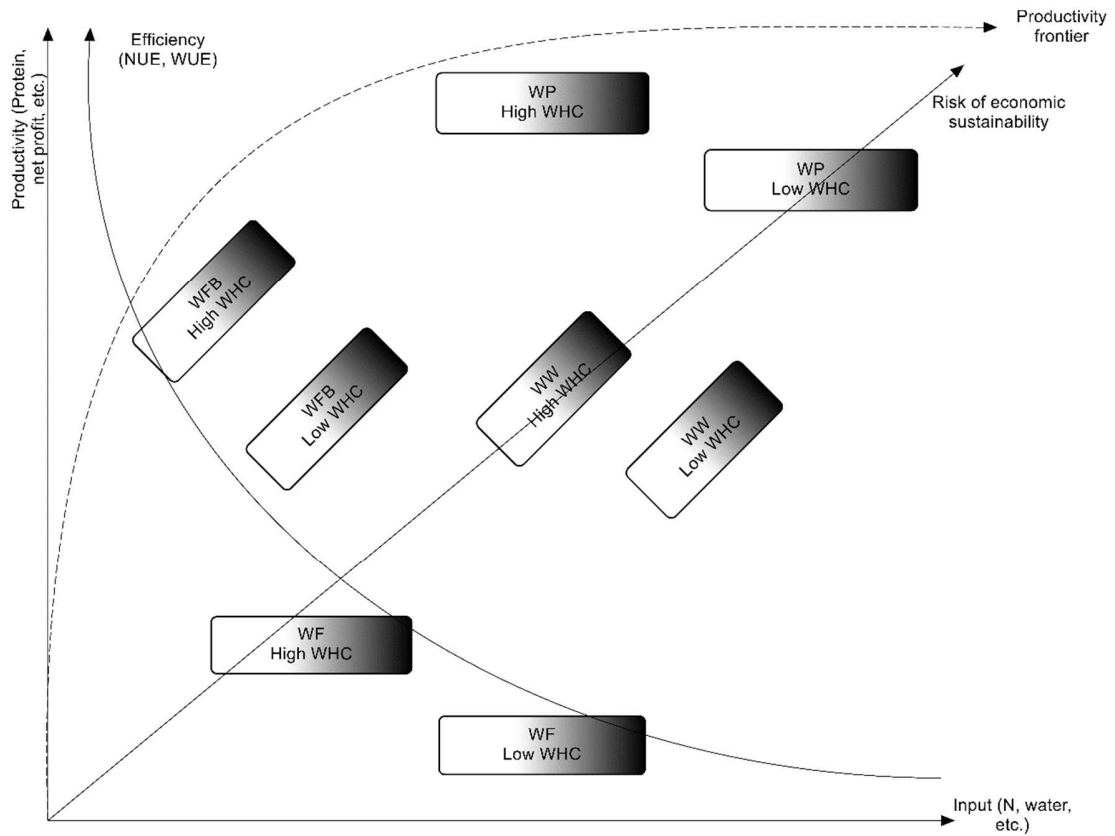


Fig. 6. Conceptual guide-map defining the behavior of the most widespread cropping systems taking into account the inputs of the wheat crop, rotational outputs, wheat efficiency, and economic risk of low relative productivity. WW, WF, WP and WFB correspond to wheat-wheat, wheat-fallow, wheat-potato, and wheat-fava bean rotations, respectively. The darker the represented system area, the more intensive the management system.

Table 1. Winter wheat reference plot characteristics.

Plot ID	Sowing date	Harvesting date	Sowing density (Seeds m <sup>-1</sup> )	N applied (kg ha <sup>-1</sup> )	Irrigation applied (mm)	Soil WHC
1	23/11/2018	02/07/2018	480	230	100	low
2	20/11/2018	05/07/2018	480	170	240	high
3	20/11/2018	01/07/2018	480	170	160	low
4	15/11/2018	01/07/2018	430	280	90	high
5	23/11/2018	28/07/2018	465	180	0	high

Table 2. Mean and standard deviation results of the in-situ measurements of wheat plots. The measurements correspond to above ground biomass (AGB), above ground nitrogen (AGN), and soil water content (SWC). The measurements took place at 5 physiological stages (1: sowing, 2: tillering, 3: booting, 4: flowering and 5: physiological maturity).

Plot ID	Physiological Stage	AGB (kg ha <sup>-1</sup> )		AGN (kgN ha <sup>-1</sup> )		SWC (m <sup>3</sup> m <sup>-3</sup> )	
		Mean	SD	Mean	SD	SD	Mean
1	1					0.05	0.39
1	2	390	138	28.2	2.8	0.02	0.39
1	3	2527	126			0.02	0.4
1	4	6410	537	196.7	8.2	0.08	0.38
1	5	9975	722			0.05	0.32
2	1					0.03	0.26
2	2	513	30.5	26.2	1.6	0.05	0.36
2	3	2513	533			0.02	0.35
2	4	6290	377	287	17	0.02	0.34
2	5	10852	577			0.03	0.33
3	1					0.07	0.26
3	2	600	56	28.8	2.7	0.05	0.35
3	3	2817	241			0.03	0.34
3	4	5987	163	250.2	6.8	0.03	0.36
3	5	11338	463			0.02	0.36
4	1					0.03	0.26
4	2	529	58	21.1	2.3	0.03	0.29
4	3	2330	261			0.02	0.34
4	4	5557	681	222.3	27.2	0.02	0.29
4	5	8050	349			0.03	0.26
5	1					0.03	0.41
5	2	660	65	23.8	2.3	0.02	0.4
5	3	2980	356			0.02	0.38
5	4	5343	218	224.1	9.1	0.03	0.3
5	5	8962	730			0.03	0.28

Table 3. Potato and fava bean plot characteristics. The yield is expressed in dry matter (at a standard level of moisture).

Crop and ID	Sowing date	Harvesting date	N applied (kg ha <sup>-1</sup> )	Irrigation applied (mm)	Yield (kg ha <sup>-1</sup> )
Potato 1	05/03/2018	10/07/2018	100	560	50000
Potato 2	05/03/2018	15/07/2018	193	600	37000
Potato 3	01/03/2018	21/06/2018	370	700	40000
Potato 4	10/03/2018	17/07/2018	370	500	40000
Fava bean 1	10/11/2017	05/05/2018	50	50	1201
Fava bean 2	08/11/2017	15/05/2018	50	0	945
Fava bean 3	12/11/2017	11/05/2018	0	0	1125

Table 4 Soil characteristics in where the pilot fields were selected in the mid Bekaa plain of Lebanon.

Low	Depth	Soil Class	Sand %	Clay %	OM%	BD (g	WP	FC
	(m)					cm <sup>-3</sup> )	(%Vol)	(%Vol)
Horizon 1	0.1	Cambisols	30	56	2.3	1.29	33.2	44.6
Horizon 2	0.25	Cambisols	25	55	2.2	1.28	32.6	44.1
Horizon 3	0.3	Cambisols	18	56	1.8	1.35	32.8	44.2
Horizon 4	0.4	Cambisols	25	48	1.9	1.33	33	44.4
High								
Horizon 1	0.1	Cambisols	29	55	2.6	1.3	32.6	44.1
Horizon 2	0.35	Cambisols	25	55	2.8	1.32	32.5	44
Horizon 3	0.55	Cambisols	16	50	2.2	1.28	29.6	42.2
Horizon 4	0.4	Cambisols	25	45	2	1.34	27.1	40.1

Table 5. Cropping system scenarios simulated using CropSyst. Each cropping system scenario consists of a rotation type and wheat management system. 16 cropping systems were simulated in two soil water holding capacity types, leading to 32 scenarios.

Low Soil holding capacity (LSC)			High soil holding capacity (HSC)		
Scenario	Rotation	Management	Scenario	Rotation	Management
1	Wheat-Wheat	F1-I1	17	Wheat-Wheat	F1-I1
2	Wheat-Wheat	F1-I0	18	Wheat-Wheat	F1-I0
3	Wheat-Wheat	F0-I1	19	Wheat-Wheat	F0-I1
4	Wheat-Wheat	F0-I0	20	Wheat-Wheat	F0-I0
5	Wheat-Fallow	F1-I1	21	Wheat-Fallow	F1-I1
6	Wheat-Fallow	F1-I0	22	Wheat-Fallow	F1-I0
7	Wheat-Fallow	F0-I1	23	Wheat-Fallow	F0-I1
8	Wheat-Fallow	F0-I0	24	Wheat-Fallow	F0-I0
9	Wheat-Potato	F1-I1	25	Wheat-Potato	F1-I1
10	Wheat-Potato	F1-I0	26	Wheat-Potato	F1-I0
11	Wheat-Potato	F0-I1	27	Wheat-Potato	F0-I1
12	Wheat-Potato	F0-I0	28	Wheat-Potato	F0-I0
13	Wheat-Fava bean	F1-I1	29	Wheat-Fava bean	F1-I1
14	Wheat-Fava bean	F1-I0	30	Wheat-Fava bean	F1-I0
15	Wheat-Fava bean	F0-I1	31	Wheat-Fava bean	F0-I1

16	Wheat-Fava bean	F0-I0	32	Wheat-Fava bean	F0-I0
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Table 6. Crop input costs and output prices.

Input	Cost (US\$ ha <sup>-1</sup> )	Output	Price (US\$ Ton <sup>-1</sup> )	Crop	Input cost (US\$ ha <sup>-1</sup> )	Output price (US\$ Ton <sup>-1</sup> )
Wheat						
Fertilizers	400 (SD=47)	Grain yield	360	Potato	9150 (SD= 1556)	330 (SD=43)
Water	450 (SD= 48)	Straw	50 (SD=8)	Fava bean	745 (SD= 78)	1000 (SD=114)
Labor+ Pesticides	450 (SD= 70)					
Seeds	200 (SD= 31)					

Table 7. Wheat grain yields in different soil water holding capacities (WHC), rotations and management systems in dry Mediterranean conditions. The statistically different groups are represented by different letters (a, b and c) characterizing yields with significant difference (Tukey test at  $\alpha=0.05$ ).

Management	Wheat grain yield (kg ha <sup>-1</sup> )				ANOVA Significant difference (Rotation)
	Wheat-Wheat	Wheat-Fallow	Wheat-Potato	Wheat-Fava bean	
<b>Soil with low WHC</b>					
F1-I1	4513	4374	4515	4404	a,b,a,ab
F1-I0	3787	3517	3757	3601	a,b,a,b
F0-I1	3447	3705	3962	3873	a,ab,b,b
F0-I0	3124	3141	3433	3280	a,a,b,ab
<i>Significant difference (Management)</i>	a,b,bc,c	a,b,b,b	a,b,ab,b	a,bc,ab,c	
<b>Soil with high WHC</b>					
F1-I1	6083	6246	6216	6117	a,a,a,a
F1-I0	5250	5638	5549	5525	a,a,a,a
F0-I1	5126	5818	5763	5736	a,b,b,b
F0-I0	4665	5421	5290	5200	a,b,b,b
<i>Significant difference (Management)</i>	a,b,b,b	a,ab,ab,b	a,ab,ab,b	a,ab,ab,b	