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

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Abstract

The promotion of optimum rotations and agricultural management of winter wheat-based cropping systems is very critical, as wheat is considered an essential component in the Mediterranean diet. Considering the delicate economic situation of farmers in the Mediterranean area, recommending a low risk, sustainable farming system is desirable. In this study, an innovative application of a multi-criteria field-level approach is presented, targeting food security, farmer profitability and environmental sustainability. The CropSyst biophysical simulation model was calibrated and implemented for the study site. It was chosen for its agro-environmental robustness to simulate four rotations (wheat-wheat, wheat-fallow, wheat-potato, and wheat-fava bean). Four types of wheat agricultural management systems (full fertilization and full irrigation, full fertilization and zero irrigation, zero fertilization and full irrigation, and zero fertilization and irrigation) were tested in low and high soil water holding capacity (WHC) types. The effects of soil conditions, management practices and rotation type on wheat grain yields were assessed. Furthermore, the performance of each winter wheat-based cropping system was evaluated in terms of productivity (protein production and profitability) and the efficient use of resources (nitrogen and water), as well as the economic risk of low relative productivity each one engenders. The results show that there is no particular optimal scenario that can simultaneously ensure high productivity, reduce economic risk of low relative productivity, and achieve high wheat- water- and nitrogen-use efficiency. However, the wheat-fava bean rotation cultivated with no wheat fertilization appeared to be a better substitute to the wheat-wheat rotation in terms of protein production (0.93 t/ha versus 0.8 t/ha in low WHC soil and 1.34 t/ha versus 1.17 t/ha in high WHC). This cropping system achieved a higher net profit (2111 US$/ha versus 1222US$/ha in low WHC and 3550 US$/ha versus 2450 US$/ha in high WHC), showing high resource-use efficiency and was less risky for farmers. Moreover, a very high profit could only be attained with the wheat-potato rotation (8640 US$/ha and 12170 US$/ha in low and high WHC, respectively), yet with low input-efficiency and high economic risk of low relative productivity.

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

1. Introduction

Throughout history, the Mediterranean, especially its eastern and southern parts, has been known to be the origin of many landraces and a pioneer in food production. It has never been a region of abundance and glut, yet has always overcome the deficiencies in production (Braudel, 1990; Kehoe, 1988). Winter wheat (*Triticum Durum L.)* is one of the major crops grown in the Mediterranean. In Lebanon and the Middle East and North Africa (MENA) region, wheat is often financially and sometimes technically supported as a part of the governmental subsidy system. This self-sufficiency policy has long been the bedrock of food security, leading to the continuous cultivation and successive sowing of wheat (El Khansa, 2017; Nasrallah et al., 2018). At the same time, the MENA region is the largest cereal importer in the world, with over 58 million metric tons, covering more than 50% of its consumption (Wright and Cafiero, 2010). For nations within the MENA region, importing cereal grains (mainly wheat) is not a matter of choice, but a necessity (Ahmed et al., 2014).

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

Thus, several studies have tried to address the obvious question of the performance and outputs of each production system. Diverse crop rotations have been experimented, and sometimes versus monoculture systems (Beaudoin et al., 2005; Constantin et al., 2010; Hansen et al., 2015, 2010; Macdonald et al., 2005; Moreau et al., 2012; Sieling and Kage, 2006). For instance, long-term field experiments in Central and Western Europe have shown that the inclusion of a catch crop within a rotation can indeed significantly increase nitrogen-use efficiency (NUE) as well as the N (Nitrogen) uptake of the main crop (Berntsen et al., 2006; Constantin et al., 2011). In comparing different types of wheat-based rotations, Angus et al. (2015) found that both fallow-wheat and break crop-wheat rotations generally produced greater yields than wheat-wheat rotations. For instance, legume-wheat rotations generated over 20% wheat grain yields compared to wheat-wheat rotations. Without underestimating the role of plant genetics, the efficient management of water and N has been identified as a crucial need for closing the yield gap, which is estimated by comparing the observed yield with the attainable one (Mueller et al., 2012), of main cereal crops (Sinclair and Rufty, 2012) notably on arid and semi-arid soils with low organic carbon and nitrogen content (Darwish et al., 2018). Downscaling to field and farm levels made it possible to study and analyse the economic risk that farmers and producers could face, in relation to their adopted cropping systems (Di Falco and Perrings, 2005; Komarek et al., 2015; Mahmood et al., 2017; Valle et al., 2004). However, the absence of a clear integrated approach at field level, assessing different existing wheat-based cropping systems regarding their productivity, resource-use efficiency and economic risk of low productivity, represent the motivation of this study. It raises the key issue of the wheat-based cropping systems to be promoted (regarding resources, soil types, climatic variability, and management systems). It also offers a conceptual guide-map, allowing policy-makers and producers to categorize different cropping systems with reference to productivity (i.e. net profit and protein production), efficiency (water and nitrogen) and the economic risk of low relative productivity.

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

2. Methods

2.1.Study site and crop management

The Bekaa plain in Lebanon is located between 33°33’ N and 33°60’ N latitude, 35°39’ E and 36°14’ E longitude (Fig. 1). The area of the plain is around 860.25 km² with an average elevation of 1000 m above sea level. The dominant soils within the plain are mainly clay to loam but differ in their water holding capacity (WHC). The Bekaa is characterized by a semi-arid Mediterranean climate and the average annual precipitation is around 600 mm. In addition, agriculture is the main economic activity as field crops, orchards, annual and perennial plants are cultivated.

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

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

Fertilization is supplied, especially nitrogen, being one of the most growth driving nutrient. Fertilization management practices differ among farmers, however, nitrogen is supplied in both organic and inorganic forms. In the case of wheat, farmers supply nitrogen in amounts of up to 230 kg ha^{-1} as ammonium sulfate at emergence and before the flowering stages. However, up to 15% of wheat farmers do not apply synthetic fertilization. This is mainly due to the cultivation of potato as a previous crop, where the land is supposed to be fertile enough to meet wheat nitrogen demands, besides other economic considerations and money saving purposes, when necessary. As for potato crops, nitrogen is applied before planting in the form of manure (around 250 kgN ha^{-1}), in addition to a second application of nitrogen (around 100 kgN ha^{-1}) before the inception of flowering. When fertilized, fava beans receive a triggering amount of 50 kgN ha^{-1}of nitrogen 60 days after sowing.

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

2.2.Simulation model

2.2.1. CropSyst model description

The CropSyst model, which was first presented by Stockle et al. (2003, 1994), uses weather, soil and crop input data for the estimation of crop productivity under different management conditions (water and nutrient input). It has been widely applied to many regions (e.g. USA, China, Central and Northern Europe and the Mediterranean) and crops (e.g. cereals, vegetables and legumes) (Ahmad et al., 2017; Belhouchette et al., 2008; Brooks et al., 2017; Palosuo et al., 2011; Rötter et al., 2012), especially for its ability to work on a daily basis for simulating multi-crop scenarios, in addition to water-soil dynamics (Richard's equation for our case) and nitrogen budgets.

2.2.2. Datasets for model calibration and evaluation

Experimental datasets for winter wheat model calibration and evaluation

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

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

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

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

Survey datasets for potato and fava bean model calibration and evaluation

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

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

2.2.3. Model calibration and evaluation process

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

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

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

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

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

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

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

To have proper insight on the model efficiency, the model efficiency "EF" indicator was calculated as:

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

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

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

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

where O_i represents the observed data, P_i represents the predicted data and $\bar{O}$ is the average of the observed data. The Willmott index of agreement (d) varies from 0.0 (poor model) to 1.0 (perfect model), similar to the interpretation of the coefficient of determination (R2).

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

2.3. Developing the scenarios to be simulated by the CropSyst model

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

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

F1-I1: Full fertilization (230 kgN ha^{-1}) and full irrigation (100 mm)

F1-I0: Full fertilization (230 kgN ha^{-1}) and no irrigation.

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

F0-I0: No fertilization and no irrigation.

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

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

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

Calculation of the productivity indicators

- The net profit (US$ ha^{-1}) indicator: computed at rotational level (2 years) as follows:

$$NP_r = Rev_r - Cost_r \tag{7}$$

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

In order to calculate the Rev_r and the $Cost_r$ (Eq. 7) of each of the cropping systems, data on input costs and output prices were collected through a local survey conducted at the study site (Table 6), since in Lebanon, there is a lack of national official statistical sources for annual input and output costs and prices. The input costs collected correspond to costs related to cultivation (wheat, potato or fava bean), while output prices refer to selling the produce (i.e. wheat grain yield, straw yield, potatoes, and fava bean grains). The input costs and output prices collected through our survey correspond to an average of 5 years as the prices are more or less stable and do not witness dramatic fluctuations. This also appears when comparing to FAOSTAT (http://www.fao.org/faostat/) data. Regarding the respondents, costs related to wheat were asked from 10 wheat farmers, costs related to potato were asked from 10 potato farmers and costs related to fava bean were asked from 6 fava bean farmers. The farmers were selected randomly, yet we intended to interview those who have been exercising the cultivation for a relatively long period (minimum 10 years). In addition, we aimed asking farmers who own their lands. The responses collected from these farmers (Table 6) were homogeneous by looking at the averages and the standard deviations.

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

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

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

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

where P_r is the amount of protein (kg ha^{-1}) produced by each rotation (r) (2years), $Yield_{Crop1}$ is the yield (kg ha^{-1}) of the first crop within the rotation, $Yield_{Crop2}$ is the yield (kg ha^{-1}) of the second crop within the rotation, $\%P_{Crop1}$ is the percentage of protein contained in 1 kg of the yield of crop1 and $\%P_{Crop2}$ is the percentage of protein contained in 1 kg of the yield of crop2. Equation 8 is applied 10 times for each cropping system.

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

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

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

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

Calculation of the efficiency indicators

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

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

$$WUE_{Wheat} = \frac{GY}{ET_{Actual}} \tag{11}$$

where NUE_{Wheat} is the nitrogen-use efficiency calculated for the 10-years (out of a total of 20 years) of the wheat crop. AGN_1 (kgN ha^{-1}) stands for above ground nitrogen when wheat is fertilized. $N_{Supply1}$ corresponds to the amount of supplied N fertilizer (kgN ha^{-1}), when applied. *TSM* corresponds to total soil mineralization rate accounting for N soil pool (kgN ha^{-1}). WUE_{Wheat} is the water-use efficiency calculated for the 10years (out of a total of 20 years) of wheat cultivation. *GY* corresponds to grain yield. ET_{Actual} stands for evapotranspiration (mm).

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

$$ARED_N = \frac{AGN_1 - AGN_0}{N_{Supply1} - N_{Supply0}} \tag{12}$$

$$ARED_W = \frac{GY_1 - GY_0}{W_{Supply1} - W_{Supply0}} \tag{13}$$

where $ARED_N$ and $ARED_W$ correspond to apparent recovery efficiency by difference, for nitrogen and water respectively. $N_{Supply0}$ corresponds to the amount of supplied N fertilizer (kgN ha^{-1}), when not supplied, which is equal to zero. AGN_0 (kgN ha^{-1}) corresponds to the above ground N when wheat is never fertilized. GY_1 (kg ha^{-1}) and GY_0 (kg ha^{-1}) stand for grain yield under full irrigation and no irrigation at all, respectively. $W_{Supply1}$ stands for the amount of water supplied as irrigation (mm). $W_{Supply0}$ is the amount of water supplied as irrigation (mm), when not supplied, which is equal to zero.

2.5. Calculation of the "economic risk of low relative productivity"

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

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

$$Risk_{CS} = \left(\sum_{r=1}^{Nr} W_r \times (+RD_r)\right) \times F_{r/Nr} \qquad (14)$$

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

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

$$W_r = \frac{Cost_r}{Cost_{WP}} \tag{15}$$

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

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

$$RD_r = \frac{Cost_r - NP_r}{Cost_r} \tag{16}$$

where RD_r is the relative deviation of the net profit from the cost for each rotation within each cropping system, $Cost_r$ is the variable production cost of a particular rotation (e.g. wheat-wheat in F1-I1 management system) and NP_r is the net profit of this particular rotation within a particular cropping system. It is noted that within the whole period (20 years) of simulation in a particular cropping system (10 rotations), the $Cost_r$ is fixed and doesn't change, while the NP_r changes for every rotation (2 years). If the output of RD_r is negative, meaning that the NP_r is higher than the $Cost_r$, then the corresponding rotation is neglected and is not considered when applying Eq. 14.

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

$$F_{r/Nr} = \frac{\#PositiveRD_r}{Nr} \tag{17}$$

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

3. Results

3.1. Calibration and validation of the CropSyst model

The results of the validation of the CropSyst model are therefore generated after the calibration. Following the rating proposed by Jamieson et al. (1991), the RRMSE ranged between 9.2% and 12.7%, it can thus be considered as good to excellent simulation of dry matter production (DMP). For above ground nitrogen (AGN) simulation, RRMSE ranged from 7.7% to 25.0% and can be considered as average to good. In the case of the average soil water content (SWC) simulation, RRMSE ranged from 21.0% to 34.3%. As regarding the efficiency indicator (EF), for the DMP, the values ranged between 0.946 and 0.99, between 0.9 and 0.99 for AGN and between -5.5 and -0.57 for SWC. Concerning the index of agreement (the correlation/regression indicator), the values ranged between 0.990 and 0.996 for the DMP, between 0.96 and 0.997. As for the SWC, the index of agreement produced values between 0.53 and 0.64. Hence, the calibrated model can be counted as satisfactory in terms of simulating yield, water, and nitrogen cycles.

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

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

In low WHC soil, wheat grain yields produced by a wheat-potato rotation were the highest (with no clear effect of the rotation type). However, in all rotations, wheat grain yields significantly decrease as the input amounts (fertilization and irrigation) decrease or are not applied (e.g. in the case of a wheat-potato rotation it drops from 4515 kg ha^{-1} in F1-I1 to 3433 kg ha^{-1} in F0-I0.

When wheat is fertilized with no irrigation (F1-I0), wheat grain yields in a wheat-wheat rotation (3787 kg ha^{-1}) are similar to those observed in a wheat-potato rotation (3757 kg ha^{-1}), meaning that water stress in such a soil type (low WHC) is more significant than nitrogen stress. This finding agrees with the results reported earlier (Huang et al., 2003). When wheat is not fertilized (irrigated or not), wheat grain yields in wheat-fallow and wheat-fava bean rotations are higher than those observed in a wheat-wheat rotation (e.g. 3873 kg ha^{-1} in a wheat-fava bean rotation versus 3447 kg ha^{-1} in a wheat-wheat rotation) and similar to those observed in a wheat-potato rotation (3280 kg ha^{-1} in a wheat-fava bean rotation versus 3433 kg ha^{-1} in a wheat-potato rotation). This means, indeed, that fallow and fava bean when in rotation with wheat better mitigate water and nitrogen stresses on wheat grain yields, in comparison with wheat-wheat rotation. This result is in agreement with other findings (López-Bellido et al., 2012).

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

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

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

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

To grasp the added value of input resources (water and nitrogen) on wheat grain yields, the Apparent Recovery Efficiency by Difference (ARED) for the two input resources (Keller and Keller, 1995; Rao et al., 1992) is calculated, for wheat grain yields following different previous crops (wheat, fallow, potato and fava bean) in the two soil water holding capacities (low and high) [Eqs. (12) & (13) section 2.4.1]. ARED was computed for nitrogen in both cases of irrigation (I1 and I0), as well as for irrigation in both cases of nitrogen supply (F1 and F0) (Fig. 2). The separation of means was done using 2-way ANOVA analysis (Tukey test).

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

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

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

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

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

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

3.5. Rotation performance (productivity and efficiency) and economic risk of low relative productivity

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

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

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

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

By looking at the WUE, intensive systems (except wheat-fallow rotations) are more efficient in terms of water-use than extensive systems. This result is consistent with the literature, which mentions that water is one of the most limiting factors in shallow soils of arid areas (Sultana et al., 2009). Semi-intensive and extensive systems (systems 8, 9, 11, 12, 13, 15 and 16) are then less efficient in terms of WUE. Wheat-fallow systems (especially the extensive ones: 10 and 14) are the least efficient in terms of water, basically due to large amounts of evaporated water.

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

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

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

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

4. Discussion

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

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

- Preserving deep soils for wheat cultivation: Such a strategy is achieved by combatting ongoing soil degradation, especially in dry and sub-dry areas. The presence of many typical cereal area plains in the Mediterranean region with low soil water holding capacity results in grain yield reduction due to post-anthesis terminal drought where a strong relationship was found between actual evapotranspiration in the grain filling phase and the final grain yield. (Karrou and Oweis, 2012). As an example, the soil in the Medjerda-Tunisia (Souissi et al., 2017), Saïs-Morocco (Mohamed et al., 2018) and the Bekaa plain of Lebanon (Darwish et al., 2006b) typical cereal plains are more than 60% characterized by a low water holding capacity.

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

- Reduction of the areas dedicated to wheat-fallow cropping systems (WF in Fig.5): such a cropping system is characterized by low economic and nutritional performances compared to other cropping systems. This explains why this system has gradually disappeared from arid areas, and only exists for those practicing multiple activities (MoA, 2010). For those farmers, the advantage of this system is that it requires very few inputs (particularly in high WHC soils) and especially involves very little risk compared to other cropping systems. Today, in the Mediterranean region, even if the areas dedicated to this type of rotation are less common than those dedicated to other rotation types, half of the land is left uncultivated each year (López-Bellido and López-Bellido, 2003). Most of the current intensification policies in dry areas encourage the mobilization of more inputs by totally or partially subsidizing access to irrigation water, fertilizers, seeds, etc. By promoting wheat-based alternative systems other than wheat-fallow, it is potentially possible, according to our results, to increase rotational (2 year) protein production by at least 50%, at the Bekaa plain level.

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

- Switching from wheat-wheat rotation to wheat-legume crops (fava bean in our study): The wheat-legume rotation has shown better productivity than the wheat-wheat system, significantly higher efficiency (nitrogen and water) and much lower economic risk. Such findings were not very surprising as diversified rotations with catch crops usually yield high NUE (Beaudoin et al., 2005; Hansen et al., 2015; Moreau et al., 2012). Growing winter wheat with low inputs leads to a small sacrifice in terms of productivity, which may be a reason why farmers prefer intensified wheat-wheat cropping systems. Apart from fertilization, mechanization limitations in legumes cultivation and the dependence on labour (weeding, harvesting) and establishments (e.g. storage warehouses), which would be pricey if not already owned by the farmer, are also obstacles preventing farmers from an easy switch to wheat-legume rotations. Moreover, fava beans production is a local product, which is sold locally and thus linked to the national level. This could be attributed to the low-trust that is given by farmers regarding national and local markets fearing "unlawful speculation". Instead, many of them would prefer investing in wheat cultivation knowing in advance that the prices will not witness any change (even if negligible), as the government buys the grain yield.

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

Conclusions

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

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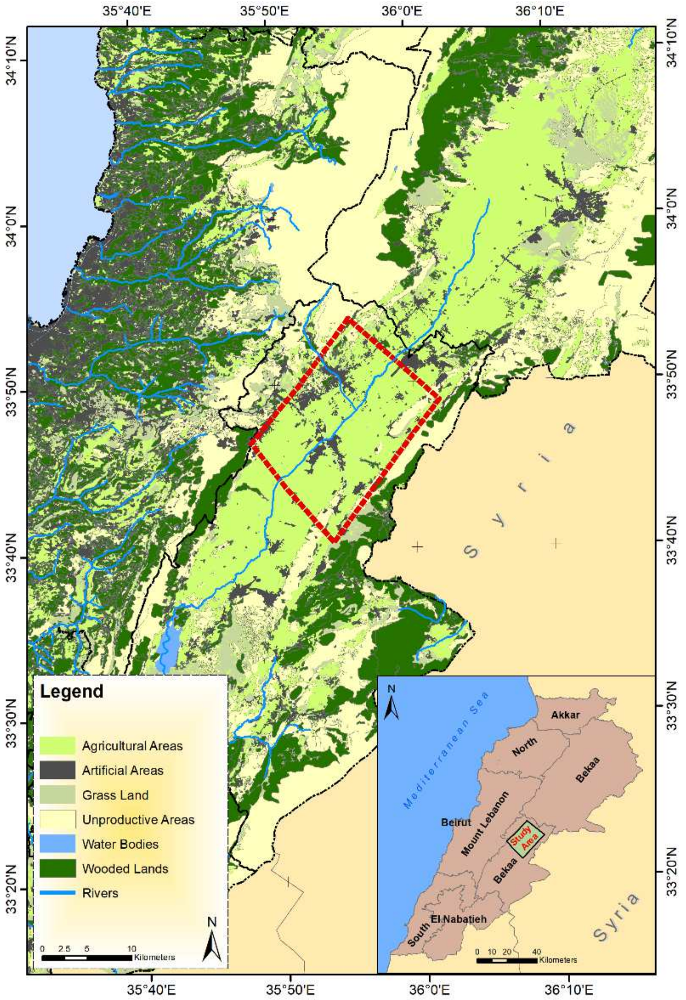
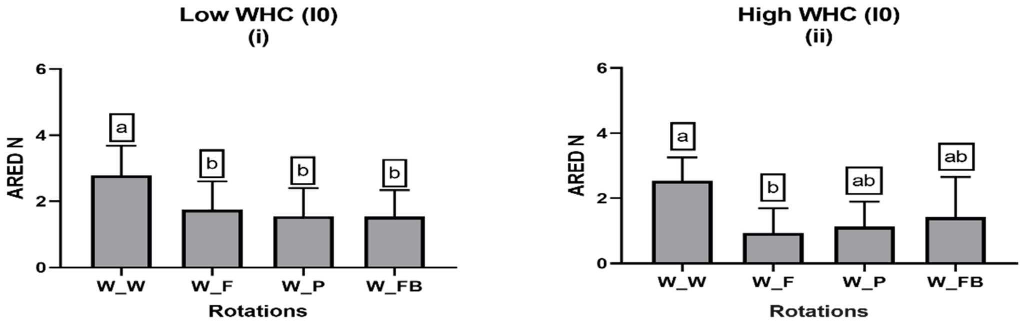


Fig. 1. Location of the Bekaa plain in Lebanon as well as the study area within the red tile



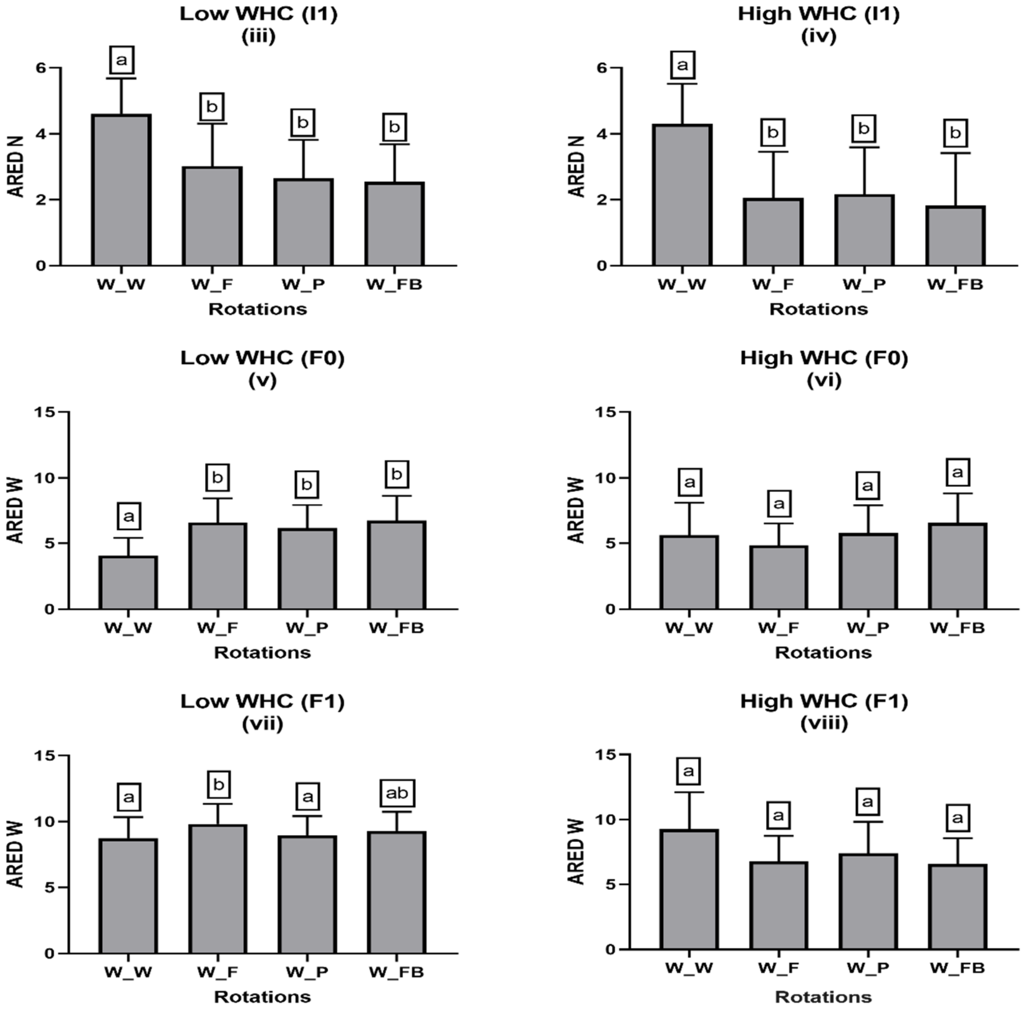
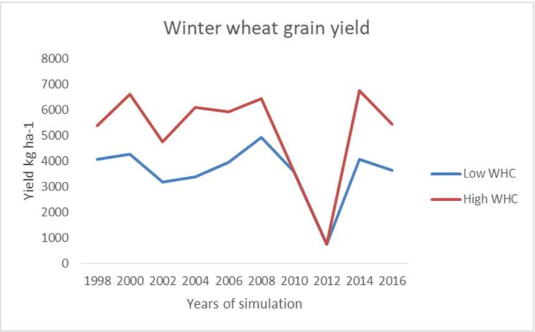
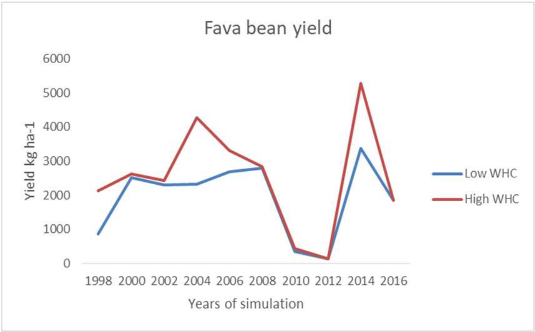


Figure 2. Apparent Recovery Efficiency by Difference (ARED) of nitrogen and irrigation of wheat crops, within each rotation, soil, and management type. a, b and c are symbols characterizing ARED which are significantly different or not regarding rotation.





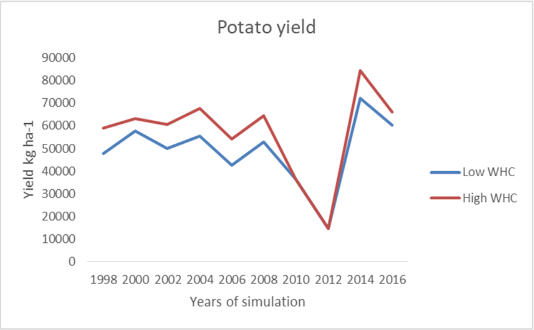


Figure 3. General yield (kg ha^{-1}) trends of the three crops simulated over the 10 rotations in both WHC soils.

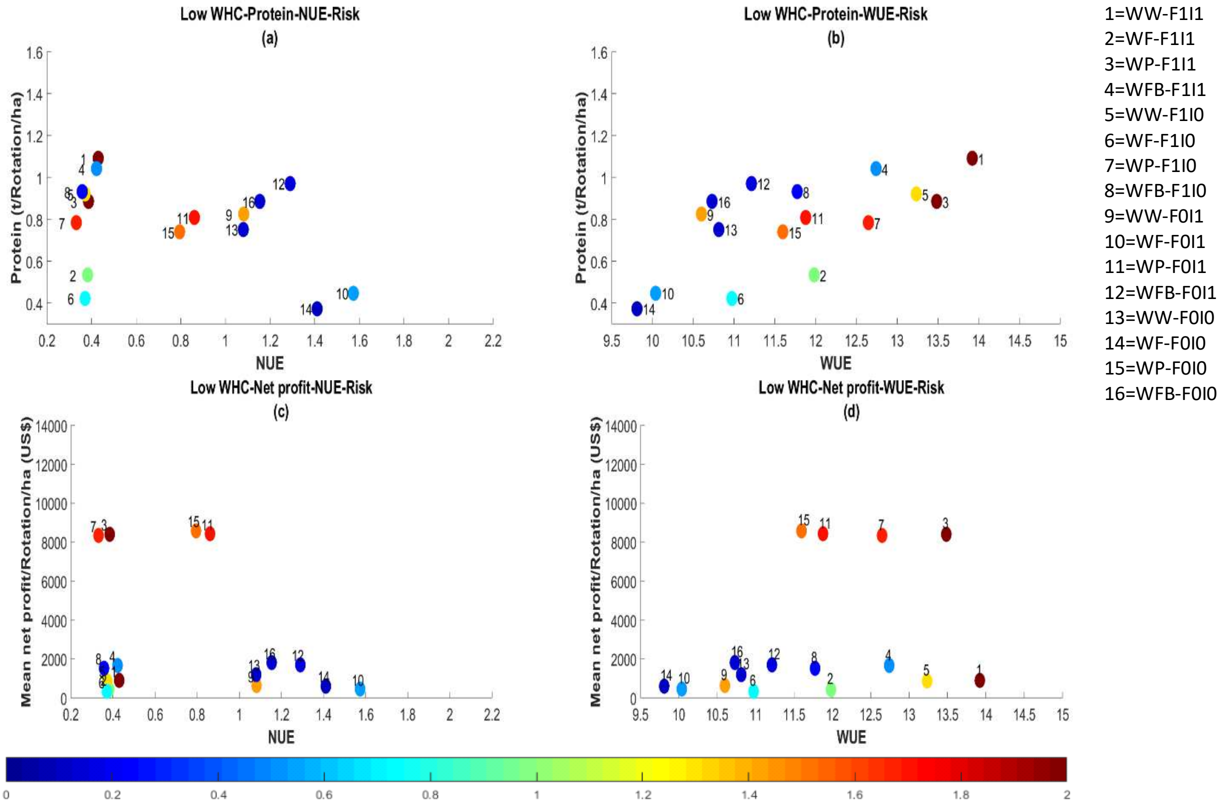


Figure 4. Risk representation of each of the cropping systems in low WHC soil denoted by the scale bar from dark blue (not risky at all) to dark red (very risky). The variation of protein production at rotational level versus wheat NUE (a) and wheat WUE (b), the variation of net profit at rotational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

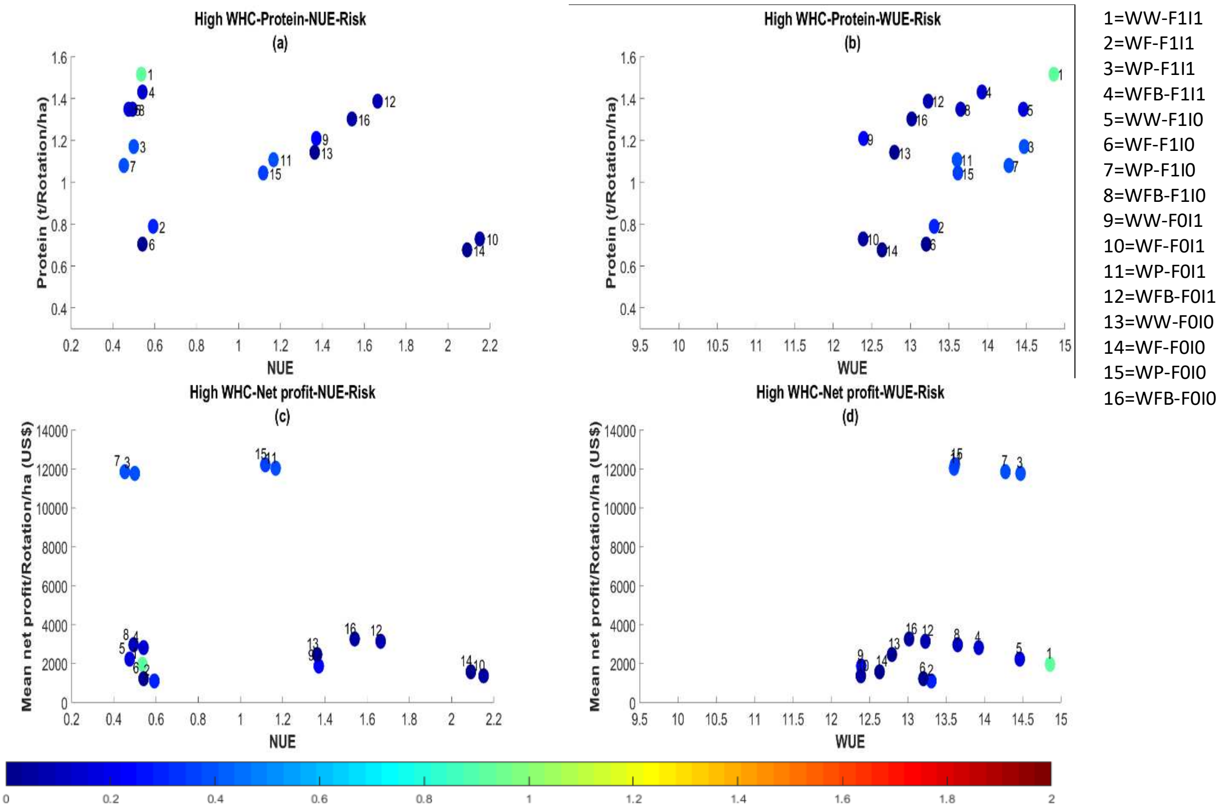


Figure 5. Risk representation of each of the cropping systems in high WHC soil denoted by the scale bar from dark blue (not risky at all) to dark red (very risky). The variation of protein production at rotational level versus wheat NUE (a) and wheat WUE (b), the variation of net profit at rotational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

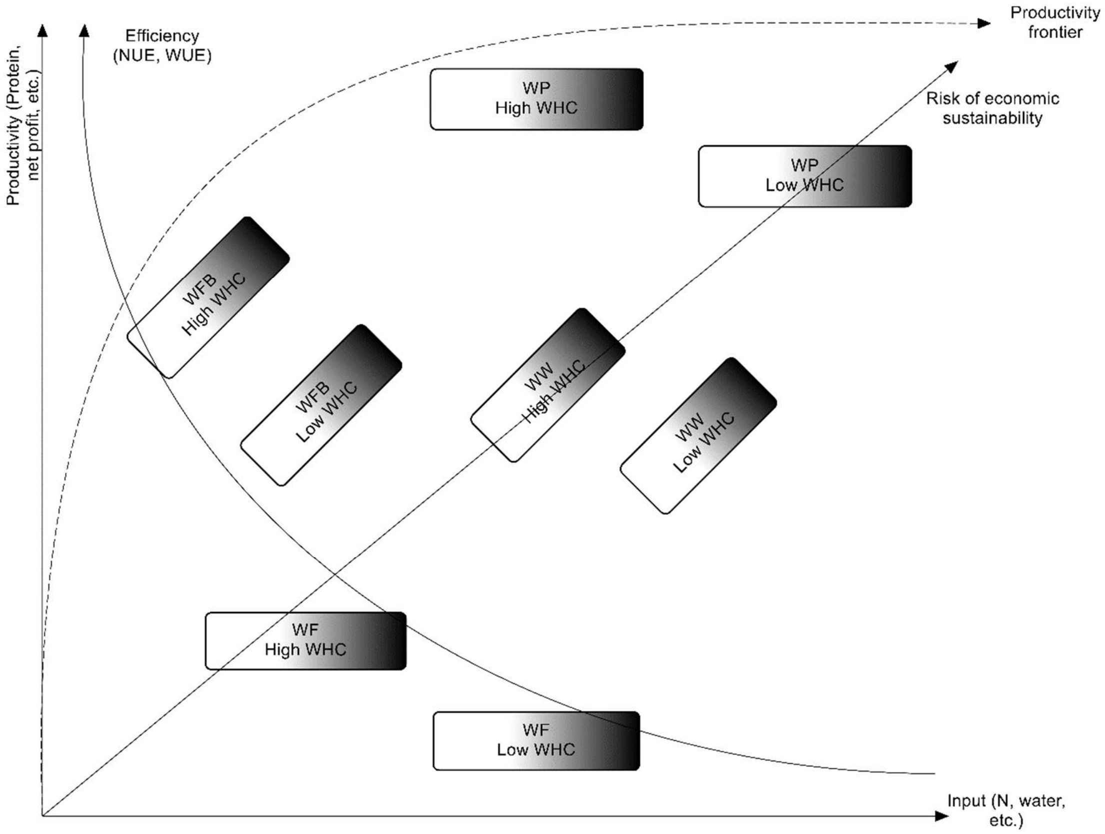


Fig. 6. Conceptual guide-map defining the behavior of the most widespread cropping systems taking into account the inputs of the wheat crop, rotational outputs, wheat efficiency, and economic risk of low relative productivity. WW, WF, WP and WFB correspond to wheat-wheat, wheat-fallow, wheat-potato, 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^{-1})	N applied (kg ha^{-1})	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^{-1})		AGN (kgN ha^{-1})		SWC (m^3 m^{-3})	
		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^{-1})	Irrigation applied (mm)	Yield (kg ha^{-1})
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

Fava bean 4	18/11/2017	12/05/2018	0	0	1342

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

Low	Depth (m)	Soil Class	Sand %	Clay %	OM%	BD (g cm$^{-3)}$	WP (%Vol)	FC (%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

Table 6. Crop input costs and output prices.

Input Wheat	Cost (US$ ha^{-1})	Output	Price (US$ Ton^{-1})	Crop	Input cost (US$ ha^{-1})	Output price (US$ Ton^{-1})
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).

	Wheat grain yield (kg ha^{-1})				
Management	Type of rotation				ANOVA
	Wheat-Wheat	Wheat-Fallow	Wheat-Potato	Wheat-Fava bean	Significant difference (Rotation)
Soil with low WHC					
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
Significant difference (Management)	a,b,bc,c	a,b,b,b	a,b,ab,b	a,bc,ab,c	
Soil with high WHC					
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
Significant difference (Management)	a,b,b,b	a,ab,ab,b	a,ab,ab,b	a,ab,ab,b	