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Research Article

Interaction of cultivar and irrigation on mixtures of wheat (*Triticum aestivum* L.) with pea (*Pisum sativum* L.)

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Abstract

Intercropping is the simultaneous cultivation of two or more crops species in the same space for a considerable proportion of the growth period. Intercropping has several advantages and is used in both traditional and sustainable agriculture. The objective of the present study was to study the interactions among different pea and wheat cultivars and the effect of water availability on wheat-pea mixtures and the competition between the two species. The experiment was conducted for two successive growing seasons using two different irrigation regimes and two cultivars from each species. The different treatments were evaluated using morphological and agronomic characteristics. Intercropping treatment, cultivars, and irrigation level affected most of the characteristics that were studied and the competition between the two species. Biomass was higher by 47% and leaf area index by 34% under irrigation compared to the rainfed conditions. The different cultivars showed different response under the two water regimes. Based on the intercropping indices, the mixture 'Yecora E' - 'Isard' is favoured under irrigation while the combination 'Elissavet' - 'Isard' under low water availability. There was interaction between cultivars and irrigation and using different cultivars in intercropping can have higher yield advantage than monocropping by exploiting the environmental resources more efficiently. Therefore, the use of appropriate cultivars in mixtures can affect the growth, biomass yield and competition between the two species leading to higher yield and greater economic return.

Keywords: biomass; competition; intercropping indices; leaf area index; radiation use efficiency; yield

Introduction

Intercropping is an old cropping practice, possibly as old as the settled agriculture. It is widespread especially in low-input cropping systems and is practiced in both traditional and sustainable agriculture. In addition, there is an increased interest in intercropping in recent years because it ensures higher or more stable yield with lower inputs and at the same time it provides important ecosystem services achieving ecological intensification (Stomph *et al.*, 2020; Lv *et al.*, 2021; Maitra *et al.*, 2021; Justes *et al.*, 2021). One of the most popular intercropping practices is the cultivation of mixtures of annual legumes with cereals which are used extensively for forage production (Lithourgidis *et al.*, 2011a; Bedoussac *et al.*, 2015; Brooker *et al.*, 2015;

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Stomph *et al.*, 2020; Maitra *et al.*, 2021; Justes *et al.*, 2021), however other intercropping systems are also used across Europe with specific advantages as it increases total productivity per crop, per area and per time. Moreover, there is greater attention in the use of intercropping systems for food combining appropriate mixtures and management practices in order to provide more food for the growing world population (Lv *et al.*, 2021; Maitra *et al.*, 2021). Therefore, there is a rising demand for using intercropping systems and the selection of the appropriate cultivars becomes an important issue.

Intercropping systems are very complex and are affected by several factors such as the species used, cultivar selection, seeding ratios, and management practices such as tillage, fertilization, irrigation, sowing time and sowing pattern (Lithourgidis *et al.*, 2011a; Bedoussac *et al.*, 2015; Brooker *et al.*, 2015; Fernandez *et al.*, 2015; Pelzer *et al.*, 2016; Amanullah *et al.*, 2020; Stomph *et al.*, 2020; Justes *et al.*, 2021). In Mediterranean countries the widely used intercropping system includes a winter cereal and a winter legume (Lithourgidis *et al.*, 2011a; Bedoussac *et al.*, 2015; Brooker *et al.*, 2015; Maitra *et al.*, 2021). A number of different cereals have been used such as wheat, barley, and oat and seem to be appropriate for intercropping with different grain legumes such as pea, faba bean, and common vetch (Lithourgidis *et al.*, 2011a; Bedoussac *et al.*, 2015; Brooker *et al.*, 2015; Pellicano *et al.*, 2015; Lv *et al.*, 2021).

There are several interactions that exists between the different species or cultivars in intercropping systems. It was proposed that there are four interactions that can exist in these systems and are described as the "four Cs" principles. Competition, Complementarity, Cooperation, and Compensation (Bedoussac *et al.*, 2018; Justes *et al.*, 2021). The most important interaction is competition and occurs for resources such as water, light, and nutrients etc. (Bedoussac *et al.*, 2018; Justes *et al.*, 2021). In order for an intercropping system to be productive, competition should be kept to a minimum and utilize the environmental resources more efficiently leading to higher yield (Stomph *et al.*, 2020; Justes *et al.*, 2021).

Competition is the predominant interaction in the intercropping systems and the competitive dynamics and the factors that influence them have been thoroughly investigated (Vandermeer et al., 1990; Lithourgidis *et al.*, 2011b; Fernandez *et al.*, 2015; Monti *et al.*, 2016; Pelzer *et al.*, 2016; Amanullah *et al.*, 2020; Justes *et al.*, 2021). Several indices have been used to describe the competition between the different crop species that are used in intercropping systems. The indices that were used are land equivalent ratio (LER), relative crowding coefficient (K), competitive ratio (CR), aggressivity (A), actual yield loss (AYL), intercropping advantage (IA) and monetary advantage index (MAI) and have been developed to describe competition and economic advantage in intercropping (Willey, 1979; Banik, 1996; Ghosh, 2004; Midya *et al.*, 2005; Dhima *et al.*, 2007; Lithourgidis *et al.*, 2011b). However, these indices have not been used in intercropping systems where the water availability is tested, to evaluate the competition among species, the competitive effects, the competition intensity, the outcome of competition and the economic advantage of each intercropping system.

Drought is one of the most important limiting factors on crop yield in many areas of the world and especially in the Mediterranean area (Blum, 2011; del Pozo *et al.*, 2019). In addition, climate change creates new challenges for crop plants as there is an increase in extreme conditions and especially a shortage of water supply (Blum, 2011; del Pozo *et al.*, 2019). Therefore, it is important to adopt techniques and management practices that will reduce the use of water and increase the water use efficiency by the crops (Blum, 2011). Genetic improvement can develop new cultivars with high yield potential and better adaptation to water deficit conditions. In addition, agronomic practices, such as tillage systems and crop residue management that promotes water infiltration and accumulation in the soil, crop rotation, adjustment of sowing time, use of cropping systems that are more resilient in climate change such as intercropping of winter cereals with legumes, are the most immediate strategy (Blum, 2011; Monti *et al.*, 2016; Bedoussac *et al.*, 2018; del Pozo *et al.*, 2019; Stomph *et al.*, 2020; Maitra *et al.*, 2021; Sohail *et al.*, 2021; Pankou *et al.*, 2021). Also, at the farming system level, the adaptation strategies should implement farmer behaviour and economic incentives which also can have a more immediate effect (del Pozo *et al.*, 2019; Maitra *et al.*, 2021). In addition, it was found that intercropping can be affected by water availability and also by the selection of the appropriate cultivar which can affect the productivity of the intercropping system and also water use efficiency (WUE) (Pankou *et al.*, 2021). However, it was not determined how intercropping can increase WUE and also how the water availability can affect the competition between the different species in an intercropping system.

The objective of the present study was to determine i) the effect of water availability on morphological characteristics and growth of the different cultivars used in intercropping systems, ii) the effect of genotype and water supply on competition indices between the two species that are used in the intercropping systems, iii) to assess which system is better for resource management with respect to productivity, competition, and economic parameters.

Materials and Methods

Experimental site

The experiment was conducted at the University farm of Aristotle University of Thessaloniki (40°32'9"N, 22°59'18"E, 0 m) for two growing seasons (2017-2018 and 2018-2019). The soil was a clay loam (sand 30%, clay 35% and loam 35%) with 45 mg NO_3 kg^{-1} content, 25 mg kg^{-1} P (Olsen), organic matter 10 g kg^{-1}, pH (1:1 H_2O) 8.1, EC (dS m^{-1}) 0.621, and $CaCO_3$ 5.0%. The previous crop was winter barley (*Hordeum vulgare* L.) and after harvest the straw was baled and removed. The tillage system that was used was the conventional and the soil was moldboard plowed, harrowed and finally a cultivator was used. Weeds were controlled with hand weeding and tilling. The weather conditions were recorded and were reported as mean monthly data for both years (Figure 1).

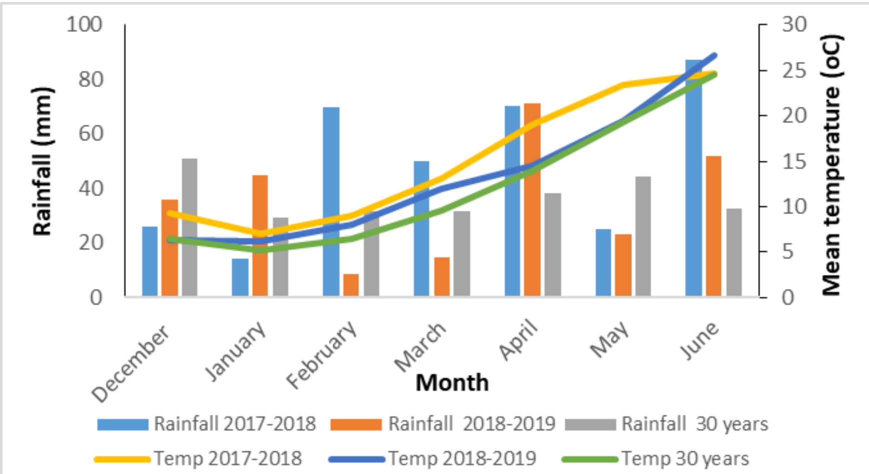

Figure 1. The main weather parameters (mean temperature and rainfall) for the two growing seasons 2017-2018 and 2018-2019 of experimentation at Thermi, Greece and its comparison to the 30-year average
The weather data were recorded with an automatic weather station close to the experimental site

Experimental design and crop management

The experimental design that was followed was the Randomized Complete Block Design (RCBD) in a split-split plot arrangement, where irrigation levels were the main plots, cultivar combinations were the subplots. In addition, we used three replications (blocks) per treatment combination and each block was divided in two strips which were the two irrigation levels and within each strip the eight treatments were randomized. Every plot was 4 m in length and 1.25 m in width with five rows 25 cm apart and the total size of each plot was 5 m^2. The crop species were sown manually.

Two different crop species were used pea and wheat and also two different cultivars from each species. The cultivars that were used from pea was 'Isard' which is an afila type and 'Olympos' which was a fully leaf cultivar. From wheat two cultivars also used, 'Yecora E' which is an early cultivar and 'Elissavet' a mid-late cultivar. Also, 'Elissavet' was taller than 'Yecora E'. The monocrops and the intercrops of both species were sown on the first week of December for both growing seasons 2017-2018 and 2018-2019. The ratio that was used was 75:25 (pea:wheat) based on seed weight. The seed quantity for each species in the mixtures was calculated based on previous experiments that were conducted in the area (Lithourgidis *et al.*, 2011b; Pankou *et al.*, 2021). More specifically, the seeding ratio that was used for the pea-wheat intercrops were 112 kg ha^{-1} and 38 kg ha^{-1} respectively.

In addition, two irrigation treatments were applied, one was with no irrigation (rain-fed) and the other one was a drip irrigation system where its sprayer spaced 50 cm apart and the rate of water supply was 4 L h^{-1} per sprayer. The irrigation lines were placed every other row. In order to calculate the amount of water applied, the FAO Penman-Monteith equation was used as it was described before taking into consideration the weather conditions (Figure 1) (Kalamartzis *et al.*, 2020b; Pankou *et al.*, 2021).

Above ground biomass determination

Biomass was determined at full bloom by cutting one square meter and weighted before and after drying it. A subsample of 0.5 kg biomass was dried at 65 °C to constant weight to determine the relative water content and the dry weight yield.

Leaf area index

Leaf area index (LAI) was recorded at growth stage 69 according to Zadoks scale system using the AccuPAR system (model LP-80, PAR/LAI Ceptometer, Decagon Devices, Inc., Pullman, WA). For the determination of LAI one measurement of Photosynthetically Active Radiation (PAR) was taken above the canopy and three measurements of PAR were taken at the soil level following the manufacturer's recommendation.

Plant height

Plant height was determined twice at growth stages 41 and 69 according to Zadoks scale system by measuring the height of ten randomly selected plants per plot from the soil to the top of the plant and getting an average value for each plot.

Radiation use efficiency

Radiation use efficiency (RUE; g MJ^{-1}) of intercrops and monocrops was calculated by dividing the biomass that was produced by the cumulative radiation interception that was measured over the growing period of the experiments according to Elhakeem *et al.* (2021).

Competition indices and monetary advantages

The advantage of intercropping and the effect of competition among the different species, cultivars and irrigation treatments were calculated using a number of different competition indices that were used before in intercropping systems (Dhima *et al.*, 2007). The land equivalent ratio (LER) was used as the criterion for mixed stand advantage compared to both pea and wheat monocrops under the irrigated and non-irrigated conditions. More specifically LER values show the efficiency of intercropping for utilizing the environmental resources compared with monocropping and the value of unity is the critical value. Therefore, when the LER value is greater than one the intercropping favors the growth and yield of the species. In contrast, when LER is lower than one the intercropping negatively affects the growth and yield of the plants grown in mixtures (Mead and Willey, 1980; Ofori and Stern, 1987; Caballero *et al.*, 1995). The LER was calculated as:

$$LER = LER_{pea} + LER_{wheat}, \quad \text{(Eq.1)}$$

$$LER_{pea} = Y_{pw}/Y_p \quad \text{(Eq.2) and}$$

$$LER_{wheat} = Y_{wp}/Y_w \quad \text{(Eq.3)}$$

where Y_p and Y_w are the yields of pea and wheat cultivars, respectively, as sole crops and Y_{pw} and Y_{wp} are the yields of pea and wheat, respectively, as intercrops.

Another coefficient that is used is the relative crowding coefficient (RCC or K) which is a measure of the relative dominance of one species over the other in a mixture (De Wit, 1960). The K was calculated as:

$K = K_{pea} * K_{wheat}$ (Eq.4)

$K_{pea} = Y_{pw} * Z_{wp}/(Y_p - Y_{pw}) * Z_{pw}$ (Eq.5) and

$K_{wheat} = Y_{wp} * Z_{pw}/(Y_w - Y_{wp}) * Z_{wp}$ (Eq.6)

where Z_{pw} is the sown proportion of pea in mixture with wheat and Z_{wp} the sown proportion of wheat in mixture. When the product of the two coefficients ($K_{pea} * K_{wheat}$) is greater than one there is a yield advantage, when K is equal to one there is no yield advantage, and when it is less than one there is a disadvantage.

Aggressivity is another index that is often used to indicate how much the relative yield increase in "crop A" is greater than that of "crop B" in an intercropping system (McGilchrist, 1965). The aggressivity is derived from the equation:

$A_{wheat} = (Y_{wp}/Y_w * Z_{wp}) - (Y_{pw}/Y_p * Z_{pw})$ (Eq.7)

if $A_{wheat} = 0$, both crops are equally competitive, if A_{wheat} is positive then the wheat cultivars are dominant, if A_{wheat} is negative then the wheat cultivars are the dominated species. Accordingly, aggressivity for pea can be derived from the equation:

$A_{pea} = (Y_{pw}/Y_p * Z_{pw}) - (Y_{wp}/Y_w * Z_{wp})$ (Eq.8)

Also, competitive ratio (CR) is another way to assess competition between different species. The CR gives a better measure of competitive ability of the crops and is also advantageous as an index over K and aggressivity (Willey and Rao, 1980). The CR simply represents the ratio of individual LERs of the two component crops and takes into account the proportion of the crops in which they are initially sown. The CR is calculated according to the following formula:

$CR_{pea} = (LER_{pea}/LER_{wheat}) * (Z_{wp}/Z_{pw})$ (Eq.9)

$CR_{wheat} = (LER_{wheat} / LER_{pea}) * (Z_{pw} / Z_{wp})$ (Eq.10)

Moreover, Banik et al. (2000) reported that the actual yield loss (AYL) index gave more precise information about the competition than the other indices between and within the component crops and the behavior of each species in the intercropping system, as it is based on yield per plant. The AYL is the proportionate yield loss or gain of intercrops in comparison to the respective sole crop, i.e., it takes into account the actual sown proportion of the component crops with its pure stand. In addition, partial actual yield loss (AYL_{pea} or AYL_{wheat}) represents the proportionate yield loss or gain of each species when grown as intercrops, relative to their yield in pure stand. The AYL is calculated according to the following formulas (Banik, 1996):

$AYL = AYL_{pea} + AYL_{wheat}$, (Eq.11)

$AYL_{pea} = \{[(Y_{pw}/X_{pw})/(Y_p/X_p)] - 1\}$ (Eq.12)

and $AYL_{wheat} = \{[(Y_{wp}/Z_{wp})/(Y_w/Z_w)] - 1\}$ (Eq.13)

The AYL can have positive or negative values indicating an advantage or disadvantage accrued in intercrops when the main objective is to compare yield on a per plant basis.

Moreover, none of the above competition indices provides any information on economic advantage of the intercropping system. For this reason, the monetary advantage index (MAI) was calculated as:

MAI = (value of combined intercrops) x (LER-1)/LER (Eq.14)

The higher the MAI value the more profitable is the cropping system (Ghosh, 2004).

Also, intercropping advantage (IA) was calculated using the following formula (Banik *et al.*, 2000):

$IA_{wheat} = AYL_{wheat} \times P_{wheat}$ (Eq.15) and

$IA_{pea} = AYL_{pea} \times P_{pea}$ (Eq.16)

where P_{wheat} is the commercial value of wheat and P_{pea} is the commercial value of pea.

Statistical analysis

All data (biomass yield, plant height, leaf area index, competition indices) were subjected to analysis of variance (ANOVA) according to the model that involves the effects (main and interactions) of three factors: 2 "growing seasons" × 2 "irrigation levels" × 8 "intercropping treatments". The experiment design that was used was the randomized complete block design (RCBD) in a split-split-plot arrangement, utilizing data from three blocks per combined treatment. Following, pairwise differences between treatments means were tested with the protected Least Significant Difference (LSD) criterion. The significance level of all hypothesis testing procedures was preset at $P \leq 0.05$. For all parameters, the variances were not statistically different between the growing seasons and a common LSD value (for both years) was calculated and used for mean comparisons. Since no statistically significant interaction between growing seasons and treatments was detected the mean values for both growing seasons are presented. The SPSS software (IBM SPSS Statistics 25, IBM Corp, released 2017) was used for the statistical analyses.

Results

Plant height

The two irrigation treatments did not affect plant height in the first measurement but there were significant differences between the two pea and wheat cultivars (Table 1). Although 'Elissavet' is a taller wheat variety compared to 'Yecora E' that is not confirmed at the first measurement because 'Yecora E' is an earlier and faster growing wheat variety than 'Elissavet'. In contrast, 'Olympos' was taller than 'Isard' in all cases as it was expected.

Table 1. Plant height of monocrops of wheat and pea and their intercrops that were measured under rainfed and irrigated conditions at growth stages 41 and 69 according to Zadoks scale system

Treatments	Plant height booting (cm)				Plant height heading (cm)			
	Wheat		Pea		Wheat		Pea	
	Irrigated	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed
'Yecora E'	41.3	41.9			81.3	78.6		
'Elissavet'	31.2	31.7			97.7	90.0		
'Isard'			15.6	14.6			80.3	64.72
Olympos			22.7	24.5			105.8	91.52
'Yecora E'- 'Isard'	37.1	36.0	16.2	15.5	78.7	76.3	71.9	66.55
'Yecora E'-Olympos	35.9	36.8	25.8	25.5	74.1	67.1	111.9	104.8
'Elissavet'- 'Isard'	30.6	31.1	15.4	16.1	86.5	84.1	85.8	69.5
'Elissavet'- Olympos	28.8	31.1	26.1	24.9	78.5	74.3	106.0	98.9
LSD	6.07		3.48		7.33		7.34	

Data presented are mean values with the least significant difference (LSD test, $p<0.05$)

Plant height was affected by irrigation in most treatments at the second measurement and the difference between irrigated and rainfed conditions was higher in pea than in wheat (Table 1). Pea plants under irrigated conditions were by an average 13% higher than in rainfed conditions while in wheat the plants under irrigation were higher by 6% compared to the rainfed conditions. In addition, in pea there was a wide range as the monocrops of 'Isard' and 'Olympos' were higher by 24% and 15% respectively in irrigated compared to the rainfed conditions. Pea height was increased under irrigation in all intercrop combinations compared to rainfed conditions and the greater difference was observed in 'Elissavet'-'Isard' mixture (23%). Plant height of 'Olympos' was increased in all mixtures compared to pure stand and more specifically a 15% increase was recorded in the mixture with 'Yecora E' under rainfed conditions (Table 1). 'Isard' had a similar response although, there was a reduction in plant height at the 'Yecora E'-'Isard' intercrop by 10% under irrigation.

Wheat height was affected negatively from pea competition in all mixtures and water conditions, especially in mixtures with 'Olympos'. The greater reduction (19.6%) was estimated for 'Elissavet' in its mixture with 'Olympos' at irrigated conditions.

Leaf area index (LAI)

Leaf area index was increased in all irrigated treatments, but the trend was slightly different between the monocrops and the intercropping treatments. In particular, there was an average increase by 35% in the irrigated conditions compared with the rainfed (Figure 2). The highest increase was found at monocrops of 'Elissavet' (73%), followed by 'Isard' (50%) compared to the rainfed conditions. On the other hand, intercrops were less affected by the irrigation treatment. The difference between the irrigated and rainfall treatments was 25 and 26% at the 'Yecora E'-'Isard' and 'Elissavet'-'Olympos' intercropping treatments, respectively. In addition, at the 'Elissavet'-'Isard' treatment there was no difference between the two irrigation regimes. Overall, intercrops showed higher LAI values compared with monocrops by 21 and 56% at irrigated and rainfed conditions respectively.

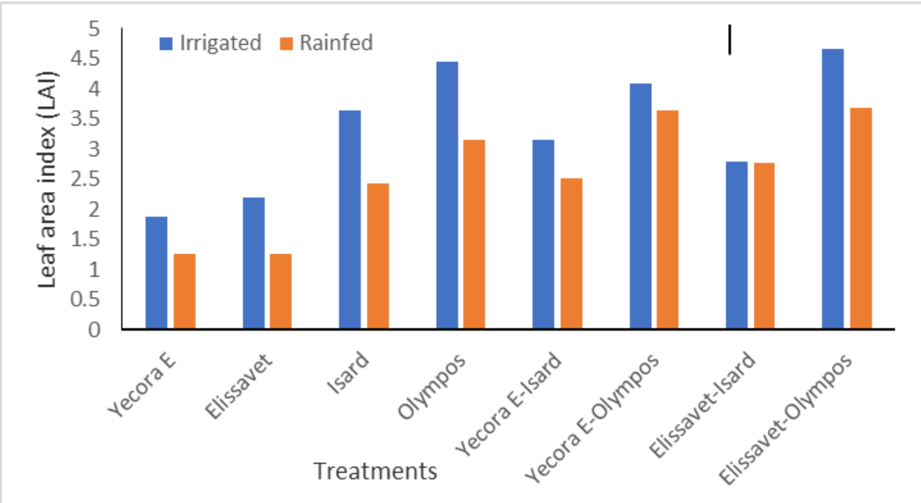

Figure 2. Leaf Area Index (LAI) of monocrops of wheat and pea and their intercrops that were measured under rainfed and irrigated conditions at growth stage 69 according to Zadoks scale system
Data presented are mean values; vertical bar corresponds to the least significant difference (LSD=0.902).

Radiation use efficiency (RUE)

Radiation use efficiency averaged over years showed that several monocrops and intercrops showed to be efficient in converting intercepted global radiation into biomass, especially under irrigation (Figure 3). The highest RUE value under irrigation was calculated for 'Elissavet'-'Olympos' intercrop (3.64 g MJ^{-1}) followed by that of 'Elissavet' (3.53 g MJ^{-1}), 'Yecora E' (3.43 g MJ^{-1}), 'Yecora E'-'Isard' (3.42 g MJ^{-1}) and 'Olympos' (3.34 g MJ^{-1}). Overall, the average RUE value for pea cultivars (2.51 g MJ^{-1}) was lower than that of wheat cultivars (2.9 g MJ^{-1}). RUE was higher at the irrigated treatments by an average of 49% and the highest difference between the irrigated and rainfed conditions was found at the 'Elissavet'-'Olympos' treatment. RUE of mixtures under rainfed conditions were similar whereas at the monocrops the highest values were estimated for both wheat and 'Olympos' monocrops while 'Isard' showed the lowest RUE. A similar trend was observed under irrigated conditions where both wheat varieties and 'Olympos' at pure stand showed similar RUE compare the monocrop of 'Isard' that had the lowest RUE.

Biomass yield

Both wheat monocrops, 'Olympos' and the intercrops of 'Yecora E'-'Isard' and 'Elissavet'-'Olympos' gave higher biomass yield compared to 'Isard' pure stand and the 'Yecora E'-'Olympos' and 'Elissavet'-'Isard' mixtures under irrigation (Table 2). The effect of irrigation was significant in all cultivation treatments and an overall increase of 47% was observed to irrigated plots compared to the rainfed ones, although the effect of irrigation varied and depended on genotypes. More specifically, the 'Elissavet'- 'Olympos' mixture produces 100% more biomass under irrigation conditions. On the contrary, the lowest difference was found in 'Yecora E'-'Olympos' intercrop as the irrigation treatment increase the above ground biomass yield only by 26% compared to rainfed conditions.

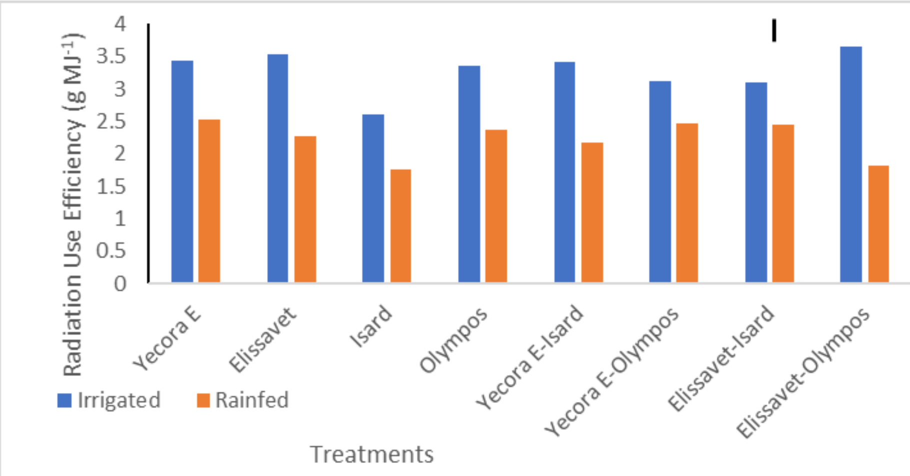

Figure 3. Radiation use efficiency (RUE; g MJ^{-1}) of monocrops of wheat and pea and their intercrops that were estimated under rainfed and irrigated conditions

Data presented are mean values; vertical bar corresponds to the least significant difference (LSD=0.482).

Table 2. Above ground biomass of monocrops of wheat and pea and their intercrops and pea contribution (%) that were measured under rainfed and irrigated conditions

Treatments	Above Ground Biomass (t/ha)						Pea contribution in Total Biomass (%)	
	Wheat		Pea		Total			
	Irrigated	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed
'Yecora E'	16.7	12.3			16.7	12.3		
'Elissavet'	17.1	11.1			17.1	11.1		
'Isard'			12.6	8.5	12.6	8.5	100	100
'Olympos'			16.3	11.5	16.3	11.5	100	100
'Yecora E'- 'Isard'	10.0	6.9	6.6	3.7	16.6	10.5	39.8	34.9
'Yecora E'-'Olympos'	5.9	6.6	9.3	5.5	15.2	12.0	61.2	45.5
'Elissavet'- 'Isard'	8.5	5.8	6.5	6.1	15.1	11.9	43.5	51.4
'Elissavet'- 'Olympos'	7.7	3.9	10.1	4.9	17.7	8.8	56.8	55.4
LSD	1.48		1.46		1.45		2.45	

Data presented are mean values with the least significant difference (LSD test, $p<0.05$)

The pea contribution to the total above ground biomass was affected by the intercropping combination and the irrigation treatments (Table 2). Overall, the mean pea contribution was increased in the irrigated treatments compared with rainfall plots with the exception of Elissavet-Isard mixture. The pea percentage in the 'Yecora E'-'Isard' intercrop increased by 14%, when it was irrigated. Furthermore, the highest pea ratio was found at the mixture 'Yecora E'-'Olympos' under irrigation, and it was 34% higher compared to the rainfed conditions.

Competition indices

Land Equivalent Ratio (LER) was calculated on biomass basis. Total LER similar to 1.00 was estimated under irrigation for the mixtures of 'Yecora E'-'Olympos' (0.91), 'Elissavet'-'Isard' (0.98) and 'Elissavet'-'Olympos' (0.94). Likewise, the LER value of the intercrops 'Yecora E'-'Isard' (1.03) and 'Yecora E'-'Olympos' (1.05) under rainfed regime did not differ significantly from monocrops (1.00). All these LER values indicate that there was neither advantage nor disadvantage of these mixtures over monocrops. The intercrops of 'Yecora E'-'Isard' under irrigation and 'Elissavet'-'Isard' under rainfall showed the highest values as they were 1.20 and 1.24, respectively. In these cases, total LER was significantly different from 1.00, which shows an advantage from intercropping over monocrops. Finally, the combination 'Elissavet'-'Olympos' had the lowest LER value (0.72) without irrigation indicating a negative interaction between the crops under scarce water resources (Table 3).

Relative Crowding Coefficient (K) is an index that is used to evaluate and compare the competitive ability of one species over the other in an intercropping system. Relative crowding coefficient values were above one in the case of rainfed conditions for the mixtures 'Yecora E'-'Isard', 'Yecora E'-'Olympos' and 'Elissavet'-'Isard' (1.45, 1.86 and 4.01 respectively) compared with the irrigated conditions. Under irrigation the highest K index was recorded for the combination of 'Yecora E' with 'Isard'. On the other hand, the lowest K value was estimated for 'Yecora E'-'Olympos' (0.71) in irrigated conditions and in 'Elissavet'-'Olympos' in rainfed regime (0.45) (Table 3).

Table 3. Land equivalent ratio (LER) and Relative Crowding Coefficient (K) based on biomass yield of wheat and pea intercrops under rainfed and irrigated conditions

Treatments	LER biomass		Relative Crowding Coefficient (K)	
	Irrigated	Rainfed	Irrigated	Rainfed
'Yecora E'- 'Isard'	1.20	1.03	2.83	1.45
'Yecora E'-'Olympos'	0.91	1.05	0.71	1.86
'Elissavet'- 'Isard'	0.98	1.24	1.07	4.01
'Elissavet'- 'Olympos'	0.94	0.72	1.32	0.45
LSD	0.140		1.198	

Data presented are mean values with the least significant difference (LSD).

Partial LER values can be used to determine the interactions between the species that are used in an intercropping system. Therefore, in Figure 4 are presented the partial LER values of biomass for pea and wheat cultivars. The left upper quadrant corresponds to situations in which pea cultivars suppressed wheat cultivars, which was shown in most mixtures, while the reverse is true in the bottom right quadrant (e.g., 'Isard'-'Yecora E' mixture under rainfed conditions). In contrast the upper right quadrant shows when the interaction between the two species is facilitation between the two species and shows higher growth, and this was shown in the 'Isard'-'Elissavet' under rainfed conditions and 'Isard'-'Yecora E' mixtures under irrigated conditions (Figure 4).

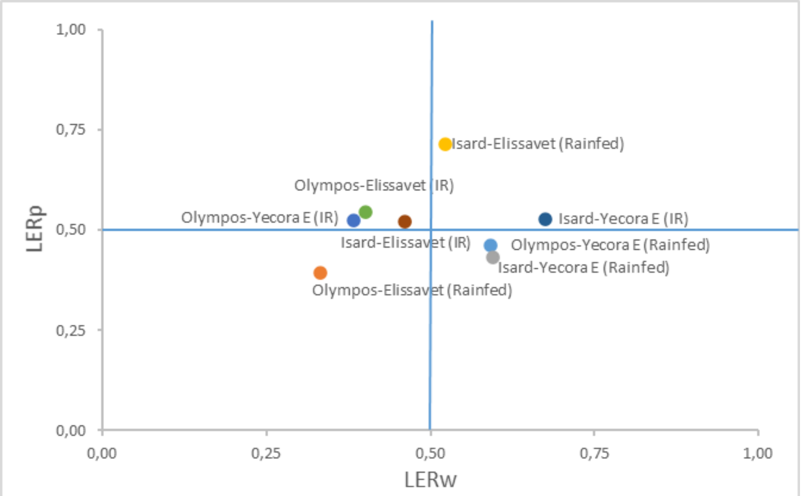

Figure 4. Partial LER values of the different intercropping systems based on biomass yield under rainfed and irrigated conditions

The relative yield advantage of each species of the mixture is expressed with aggressivity. Aggressivity index had higher values for pea compared to wheat and was the dominant species in all intercrops and water treatments (Table 4). The mixture 'Yecora E'-'Isard' had a similar performance both under low and high moist conditions. On the contrary, 'Elissavet'-'Isard' intercrop had the most diverse performance in the two water regimes.

Table 4. Aggressivity for pea (A_{pea}) and wheat (A_{wheat}) and Competitive Ratio for pea (CR_{pea}) and wheat (CR_{wheat}) based on biomass yield of wheat and pea intercrops that calculated under rainfed and irrigated conditions

Treatments	Aggressivity (A_{pea})		Aggressivity (A_{wheat})		Competitive Ratio (CR_{pea})		Competitive Ratio (CR_{wheat})	
	Irrigated	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed
'Yecora E'- 'Isard'	0.29	0.23	-0.29	-0.23	0.22	0.22	5.17	9.71
'Yecora E'-'Olympos'	0.34	0.26	-0.34	-0.26	0.38	0.23	3.26	5.55
'Elissavet'- 'Isard'	0.33	0.47	-0.33	-0.47	0.31	0.35	3.63	2.96
'Elissavet'- 'Olympos'	0.36	0.25	-0.36	-0.25	0.36	0.29	2.90	3.61
LSD	0.126		0.126		0.089		2.921	

Data presented are mean values with the least significant difference (LSD).

Competitive Ratio for pea (CR_{pea}) and wheat (CR_{wheat}) were also different under both water conditions and in all cases CR_{wheat} was higher than the respective CR_{pea}, indicating that wheat was the dominant species over pea (Table 4). Overall CR_{pea} values were quite similar between irrigated and rainfed conditions but for wheat (CR_{wheat}) there were differences between the irrigation treatments. The highest difference between the two-water regime was estimated for the 'Yecora E'- 'Isard' intercrop, since the lack of irrigation made 'Yecora E' a stronger competitor for 'Isard'. On the contrary, CRwheat values for 'Elissavet' intercrops do not differ significantly regardless of the pea variety or the irrigation treatment.

AYL is another index that can be used in an intercropping system and can describe the proportionate yield loss or gain of intercrops compared to sole crop (Table 5). In addition, AYL can provide more accurate information about the intra- and interspecific competition and behavior of the component crops. AYL_{pea}, based on biomass yield, was negative while AYL_{wheat} was higher than pea indicating that wheat was a stronger competitor than pea. Total AYL was higher for the mixture 'Yecora E'-'Isard' under irrigation whereas the lowest value was estimated under low moist conditions for the intercrop 'Elissavet'-'Olympos' (Table 5).

Table 5. AYL for pea, wheat and total based on biomass yield of monocrops of wheat and pea and their intercrops that were estimated under rainfed and irrigated conditions

Treatments	AYL_{pea}		AYL_{wheat}		Actual Yield Loss (AYL_{total})	
	Irrigated	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed
'Yecora E'- 'Isard'	-0.34	-0.46	2.38	1.98	2.04	1.52
'Yecora E'-'Olympos'	-0.34	-0.42	0.91	1.95	0.57	1.53
'Elissavet'- 'Isard'	-0.35	-0.10	1.29	1.62	0.94	1.51
'Elissavet'- 'Olympos'	-0.32	-0.51	1.00	0.64	0.68	0.13
LSD	0.191		0.410		0.432	

Data presented are mean values with the least significant difference (LSD).

Economic indices

Intercropping advantage (IA) is an index that describes the economic feasibility of the intercropping systems. In all mixtures and water conditions the estimated IA_{pea} values were negative indicating a disadvantage of pea in all cases (Table 6). On the contrary, IA_{wheat} was positive in all cases and compensated the pea disadvantage in all intercrops except from 'Elissavet'-'Olympos' under limited water availability. The IA_{total} data showed that the intercropping system of 'Yecora E'-'Isard' had the highest intercropping advantages over monoculture when irrigation was applied. Under rainfed conditions the 'Yecora E'-'Olympos' and 'Elissavet'-'Isard' intercrops had intercropping advantages compared with the irrigated conditions. The Intercropping Advantage (IA_{total}) indicated that most of intercrops (except for 'Elissavet'-'Olympos' mixture) were economic advantageous (positive values) (Table 6).

Table 6. Intercropping advantage (IA_{pea}) for pea, wheat (IA_{wheat}) and total (IA_{total}) based on biomass yield of monocrops of wheat and pea and their intercrops that were estimated under rainfed and irrigated conditions

Treatments	Intercropping Advantage[1]						Monetary Advantage Index	
	IA_{pea}		IA_{wheat}		IA_{total}			
	Irrigated	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed
'Yecora E'- 'Isard'	-81.86	-107.11	447.27	369.21	365.42	262.10	29.49	1.80
'Yecora E'-'Olympos'	-81.80	-100.18	171.71	366.89	89.91	266.71	-25.80	7.22
'Elissavet'- 'Isard'	-83.99	-24.25	236.84	299.69	152.85	275.44	-8.98	41.40
'Elissavet'- 'Olympos'	-74.97	-120.73	181.15	117.22	106.17	-3.51	-33.71	-122.24
LSD	44.32		76.48		84.23		34.23	

Data presented are mean values with the least significant difference (LSD).

[1] Average procurement price per tone of biomass for wheat= €180 and pea= €250.

A similar trend was noted when the MAI values were considered. The MAI values were positive under irrigated conditions only for the mixture 'Yecora E'-'Isard', selecting it as the most profitable intercropping combination under high water availability (Table 6). For all the other intercropping systems under irrigation the monetary advantage index had negative values. On the other hand, under limited water availability the mixtures 'Elissavet'-'Isard', 'Yecora E'-'Olympos' and 'Yecora E'-'Isard' had positive MAI values and the best intercrop was 'Elissavet'-'Isard' (41.40). Under rainfed conditions the mixture 'Elissavet'-'Olympos' had the strongest disadvantage according to MAI estimations (-122.24).

Discussion

Intercropping has been shown that have higher and more stable yield which is because of the more efficient of environmental resources and especially of nutrients, light and water than the sole crops (Justes *et al.*, 2021; Lithourgidis *et al.*, 2011a; Bedoussac *et al.*, 2015; Brooker *et al.*, 2015; Stomph *et al.*, 2020). The interactions that occur between the different species are quite complex and occur during the entire growing period that the species coexist. These interactions depend on environmental factors however the effect of water availability and also the genotypes that can be used was not determined adequately (Pankou *et al.*, 2021). In addition, there is a need to know how the competition of the different components in an intercropping system can be affected by water availability and also by the different genotypes that can be used in an intercropping system.

Plant height

In the present study it was investigated how the availability of water can affect the growth and the competition in intercropping systems of pea with wheat. Plant height is a characteristic that could be affected by the competition, the selection of plant species in an intercropping system and the management practices (Dordas and Lithourgidis, 2011; Monti *et al.*, 2016; Amanullah *et al.*, 2020). Irrigation did not affect plant height at the first measurement, but it had an impact on plant height at full bloom stage (second measurement). Irrigation increased plant height compared to limited water conditions in all cultivating systems, but pea and wheat cultivars had a different response to the irrigation treatments applied. Similar response due to water stress were reported for many other systems (Dordas *et al.*, 2018; Kalamartzis *et al.*, 2020a), however the effect of irrigation on plant height was not studied thoroughly in intercropping systems.

In all intercropping treatments, while the height of wheat plants in both cultivars was reduced, the height of 'Olympos' was increased compared with pea monocrop. This was probably because this cultivar tried to capture more light and thus overcome the strong competition of cereals (Karlidag and Yildirim, 2007; Lithourgidis and Dordas, 2010; Barillot *et al.*, 2012; Barillot *et al.*, 2014a, 2014b). Pea variety 'Isard' exhibited a similar response under intercropping except from its mixture with 'Yecora E' under irrigation, where a reduction in plant height was observed compared to monocrop. Some studies reported that plant height of legume was not affected by the intercrop treatment as plant height to monocropping was similar to that of legume in mixtures with cereal (Monti *et al.*, 2016; Sohail *et al.*, 2021). In contrast, there are several reports that found that in intercropping treatments there was an increase in plant height of legume compared to legume plants grown in monocrop (Agegnehu *et al.*, 2006; Karlidag and Yildirim, 2007; Lithourgidis and Dordas, 2010). The interactions between the different species in an intercrop can be quite complex as there is competition and also complementarity, cooperation and compensation (Bedoussac *et al.*, 2018), which can be different across the growth period of the intercropping systems. In addition, these interactions can be affected by the different management practices such as fertilization, seeding ratios of the component crops, species and cultivar selection, irrigation (Agegnehu *et al.*, 2006; Lithourgidis and Dordas, 2010; Monti *et al.*, 2016; Sohail *et al.*, 2021).

Leaf area index

Leaf area index is another characteristic that is important for intercropping systems as it affects the light capture and utilization (Barillot *et al.*, 2012; Barillot *et al.*, 2014a, 2014b). In this research, the increased water availability raised in average the leaf area index by 35% compared with the rainfed conditions. This growth was obvious in all crop systems with the exception of the mixture 'Elissavet'-'Isard', where no change was recorded with increasing irrigation. The different cultivars showed different response comparing to their respective monocrops. For all mixtures a higher leaf area index was measured compared to their respective wheat cultivars when cultivated in pure stand. The intercrops with 'Olympos' showed a slight variation on LAI depending on the wheat variety that included. On the other hand, all mixture with 'Isard' showed lower LAI values under irrigation compared to monocrop. In general, leaf area was increased in the intercropping systems (Klima *et al.*, 2020). Nevertheless, there are not enough evidence on the effect of intercropping on leaf area index (LAI) when water availability is a limiting factor. In the present study it is shown that intercrops show higher yield because of the higher LAI values especially under irrigated conditions. This is likely because of the better utilization of light as in the mixtures there is a more efficient utilization of both light and space (Barillot *et al.*, 2012; Barillot *et al.*, 2014a, 2014b).

Biomass yield

Irrigation affected positively biomass yield as it had induced a 47% increase compared with the rainfed conditions. The mixture 'Yecora E'-'Olympos' is the only exception since a reduction was measured in the biomass produced by 'Yecora E', when the irrigation was increased, probably because 'Olympos' exploited water availability better and increased competition. In any case, this disadvantage was overcome by the high pea contribution in the total yield biomass which compensated the lower wheat biomass production. Overall, some intercrops had better or similar biomass yield compared to mixtures under rainfed ('Yecora E'-'Olympos') and irrigated ('Elissavet'-'Olympos' and 'Yecora E'-'Isard') regime. Biomass production can be affected by irrigation and especially under intercropping systems (Khippal and Hooda, 2002; Farre and Faci, 2006; Al-Suhaibani, 2011; Amanullah *et al.*, 2020). The increased soil water content helped plants to grow better, have high leaf area index and utilize the environmental resources better. Intercrops showed to be more resilient to water stress with higher yield which agrees with several reports (Stomph *et al.*, 2020) and metanalysis studies which show that intercrops are more tolerant to climate change (Raseduzzaman and Jensen, 2017).

Several different studies reported that the biomass yield of mixtures between legumes and cereals were intermediate or even lower than yields of monocrops because of the high competition between the plant species or the cultivars that are used (Vandermeer, 1990; Caballero *et al.*, 1995). Similarly, others reported an increase from 20% up to 120% higher dry matter yield in pea-wheat intercrop than in wheat and pea monocrop, respectively (Barod *et al.*, 2017). When intercrops produce less than the respective intercrops this can be because of the greater number of plants per area in the monocrops (Kumar *et al.*, 2005; Barod *et al.*, 2017; Amanullah *et al.*, 2020). However, there are several other studies that found an increase in the biomass production in intercrops and also in grain production (i.e. lupin-barley, lupin-wheat, vetch-barley, vetch-wheat and pea-wheat) compared with the respective monocrop species indicating that other interactions such as complementarity, cooperation, and compensation can affect the competition between the different species and lead to an increase in the biomass (Bedoussac and Justes, 2011; Bedoussac *et al.*, 2018; Pankou *et al.*, 2021). The increase in biomass can be attributed to the more favorable environment that intercrop can create or the lower degree of competition for environmental resources (Bedoussac *et al.*, 2018).

Competition and economic indices

The estimated LER values in most cases were higher or did not differ significantly from one. The only exception is the mixture 'Elissavet'-'Olympos' that under rainfed conditions had a low LER value suggesting that the interaction of the two species in this intercrop and the competition for the limited water resources had negatively influenced the mixture yield. On the contrary, the highest values were found in irrigated treatment at the 'Yecora E'-'Isard' and at the 'Elissavet'-'Isard' under rainfed conditions. The LER ratio is used to determine the efficiency of intercropping for using the environmental resources compared with monocropping. The greatest LER in the cases of 'Elissavet'-'Isard' (1.240) and 'Yecora E'-'Isard' intercrop (1.204) indicates that up to 24 and 20 % more area would be required by a monocropping system to equal the yield of intercropping system (Ghosh, 2004; Lithourgidis *et al.*, 2011a; Pankou *et al.*, 2021). In these cases, irrigation affected total LER values which were higher than 1.00, this indicates that there is a yield advantage of intercropping over monocrops in terms of the better use of the land and environmental resources for plant growth (Mead and Willey, 1980; Chen *et al.*, 2004). LER is considered a widespread index that was used in many intercropping experiments to describe the productivity compared with monocrops however, it does not describe the interrelations between the component crops of the intercrops.

Relative Crowding Coefficient (K) estimated the relative dominance of the component crops in the intercrop. Under irrigated condition the mixture 'Yecora E'-'Isard' had the highest K index. Accordingly, when the intercrops were not irrigated the mixture 'Elissavet'-'Isard' had the highest K value compared to the rest combinations. The results indicated that under different water conditions, the intercrops that can exploit the available resources and have a yield advantage are completely different.

Aggressivity indicates that the companion crops did not compete equally in the intercropping system. Aggressivity was negative for wheat intercropping treatments while pea had positive values indicating that this can be because of pea is deep-rooted system and fixes N_2 from the soil and becomes a stronger competitor than wheat. In other studies, it was also found that one of the two components of the intercropping could compete the other more efficiently (Lithourgidis and Dordas, 2010; Amanullah *et al.*, 2020).

Competition ratio is used to describe the competitive ability of one crop over the other in an intercropping system. In particular, higher values of CR show strong competition of wheat on pea especially under rainfed conditions. Pea had lower CR values indicating that is less competitive than wheat. Cereals show higher CR values in other studies (Dhima *et al.*, 2007; Lithourgidis *et al.*, 2011a; Amanullah *et al.*, 2020) indicating that are more competitive with pea when they are sharing the same resources. In addition, it was reported that crop management can affect the competitive ratio of the different species (Dhima *et al.*, 2007; Lithourgidis and Dordas, 2010; Barillot *et al.*, 2014a).

AYL is also a useful index for the advantages and the disadvantages of intercropping. The results from our study showed that wheat had positive values compared with pea indicating that wheat was in advantage of intercropping. AYL_{total} values were different in the different cultivars and combinations indicating differences between the cultivars that were used and also in their response in irrigation. Similar differences in AYL were reported in other studies were species with bigger root systems, high statue and better adaptability to dry land conditions can give higher values of AYL (Amanullah *et al.*, 2020).

In order to describe competition between the different intercropping systems a number of different indices was estimated such as LER, K, A, CR, and partial and total AYL. These indices were developed to describe the relationship and indicate the degree of competition among the different plant species that are used in an intercrop (Lithourgidis *et al.*, 2011a). In all intercrops the CR and partial AYL values were reported higher for wheat cultivars indicating that wheat was the dominant species in all wheat-pea mixtures probably because of the positive effect of pea on wheat when grown in association (Banik *et al.*, 2000). The higher competitive ability of wheat can be attributed to the high N level in the soil that favoured the growth of wheat (Pelzer *et al.*, 2016).

In intercropping systems, it is also important the economic value of the system and the profit that can give to the producers. The IA and MAI are indicators of the economic feasibility of intercropping systems and show the most advantageous intercrops (Banik *et al.*, 2000). In this study, the IA and MAI values were the greatest in the mixture 'Yecora E'-'Isard' under irrigation and in 'Elissavet'-'Isard' under rainfed treatments respectively, which indicates that these intercropping systems had the highest economic advantage, probably due to better utilization of growth resources.

Conclusions

The present study clearly demonstrates that wheat-pea intercrops using different cultivars can have higher yield advantage of monocropping for exploiting the environmental resources. In addition, considering morphological data, biomass yield and competition and economics indices it could be concluded that the use of appropriate cultivars and combinations can provide better results, indicated by a significant advantage of intercropping which was attributed to better economics and land use efficiency than the other monocrops. Furthermore, the different irrigation treatments influenced the performance of the mixtures under evaluation and for this reason the water resources availability is a crucial factor that farmers must consider before selecting the appropriate cultivars for the implementation of an intercropping system. Therefore, intercropping is a promising approach that can be adopted by the farmers in Mediterranean areas, as intercropping systems are the most profitable, with the greatest economic return and can assist in water conservation.

Authors' Contributions

All the authors have contributed on the manuscript significantly.
All authors read and approved the final manuscript.

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Conflict of Interests

The authors declare that there are no conflicts of interest related to this article.

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