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Importance of Selection of Cultivars in Wheat–Pea Intercropping Systems for High Productivity

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Abstract: Intercropping is the cultivation of two or more crop species in the same space for a considerable proportion of the growth period. Farmers use cultivars that were bred under monoculture and there are no cultivars that have been evaluated under intercropping systems. The objective of the present study was to evaluate different cultivars of pea and wheat on intercropping systems. The experiment was conducted for two successive growing seasons (2018–2019 and 2019–2020) at the University Farm of Aristotle University of Thessaloniki, Greece, using two cultivars of field pea and six cultivars of bread wheat, and all their mixture combinations. The growing seasons, the intercropping treatments, and the cultivars affected the grain yield, the yield components, and the land equivalent ratio (LER) and actual yield loss (AYL) values. The different cultivars showed different responses under the intercropping treatments, indicating that there are cultivars that show higher grain yield in mixtures. Based on the mean grain yield for both growing seasons, the mixture 'Isard'–'Mavragani' showed higher grain yield by 86.5% and 55.7% compared with the mean grain yield of all other mixtures and monocultures, respectively. The total LER value of 'Isard'–'Mavragani' was high in both years: 1.954 and 1.693 in 2018–2019 and 2019–2020, respectively. This multicriteria evaluation of winter wheat and field pea varieties exhibited the need for the selection of appropriate cultivars for intercropping systems that were previously assessed under intercropping conditions before their exploitation from the farmers.

Keywords: grain yield; yield components; competition; intercropping indices; pea; wheat

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1. Introduction

Intercropping is a traditional farming practice that is widespread, especially in low-input cropping systems. However, there is an increasing interest in intercropping because of its significant advantages [1,2]. One of the most popular intercropping practices is the cultivation of mixtures of certain annual legumes with cereals, which are used extensively for forage production [2–5]. Nevertheless, there is also an increased interest across Europe in using these and other mixtures for food [3]. Although in temperate climates, binary mixtures have been more effective when used for forage compared to grain production, currently, there is an increased interest in using intercropping systems for food using appropriate mixtures and management practices in order to provide more food for the growing world population.

Furthermore, intercropping can provide numerous benefits, achieving ecological intensification and supporting sustainable agriculture. Intercropping systems have specific advantages such as increased total yield and land-use efficiency, improved yield stability of cropping systems, enhanced light, water, and nutrient use, and improving soil conservation and controlling weeds, insects, or diseases. Additionally, intercropping systems that combine legumes with cereals can increase the quality of forage and accelerate mechanical harvesting. However, intercropping has several disadvantages, such as the extra work required to prepare and plant the seeds, and mixed crops' lack of tolerance to herbicides [2,3].

Higher crop yield and yield stability have been found in many intercropping systems, which can be attributed to the more efficient utilization of light, water, and nutrients [2–8]. In addition, the yield advantage that was found in many intercropping systems can be attributed to the reduction of pests and diseases [9] and better weed control [10,11]. The system that is mostly used is the mixture of legumes and cereals, which can provide a number of important ecosystem services such as N_2 fixation, reduced energy consumption and greenhouse gas emissions, the improvement of physical, chemical, and biological soil fertility, and rotation. Legumes are also important for the increased need for food and feed proteins and the increased in nutritive value and the voluntary intake [3–5]. More specifically, pea–wheat mixtures exhibit higher grain yield, preserved wheat grain protein concentration, and an improved contribution of N_2 fixation to total N accumulation of pea crops compared to their sole crops, while maintaining economic and environmental sustainability [12].

Usually, intercropping systems use conventionally bred cultivars selected under monocropping systems, which are not always adapted well for intercropping conditions [3,13]. Moreover, a few studies showed that many cultivars can yield differently in the intercropping systems [14–16]. In addition, the performance of a variety/cultivar grown as a sole crop does not necessarily represent its performance in a mixed cropping system [17] due to local selection pressures generated by interspecific neighbor interactions in mixtures [13,18]. Little work has been carried out on plant-breeding approaches for species mixtures [3,13]. Therefore, it is important to find proper cultivar combinations that can have a higher yield and also to identify key traits that are important for intercropping [19]. Some theories, using functional approaches, suggest selecting lines/populations based on (i) ecological niches of species allowing the best performances and (ii) relevant "interaction traits" involving spatiotemporal interactions between species and their diversity level, including trait plasticity.

A standard "blind to traits" method evaluates the ability of the cultivar/species plants to mix by utilizing hybrid breeding procedures and quantitative genetics [20,21] for the estimation of general mixing ability (GMA) and/or the specific mixing ability (SMA) between species or cultivars of a mixture [22,23]. Since the performance of a species/variety in monocultures can strongly diverge from the performance in intercropping, it is extremely important to assess the ability of a cultivar to combine with another crop. GMA describes the mean value of a genotype to affect the mixture response, while SMA estimates the interaction of the genotype within a mixture with a specific cultivar/species. A high GMA indicates a genotype that performs well in combination with many other cultivars/species, and SMA variance is an indication of the interactions of the genotype in specific mixtures [24–26].

Finally, a commonly used index that indicates the performance of a mixture is land equivalent ratio (LER). LER is developed for the estimation of the yield advantage of a mixture and reflects the relative land area that should be used for pure stands to yield the same as mixtures. LER is an easily calculated index that indicates competitive effects and could be used for the identification of superior intercrops [27–29]. A similar index is actual yield loss (AYL) that expresses the relative yield increase or decrease of the intercropping component crops compared to the corresponding pure stand. This index is based on the actual sown proportion of the component crops [30].

Hauggaard-Nielsen and Jensen [31] evaluated pea and barley cultivars for complementarity in intercropping at different soil N levels and stated the necessity for breeding appropriate cultivars for intercropping purposes, since cultivars bred for sole cropping may not be suitable for intercropping. Bedoussac and Justes [32] assessed commonly used indices that measure intercrop durum wheat–pea efficiency. They concluded that the selection of indices and analysis of the findings are crucial in recognizing species interactions, but the results must always be associated with actual data and traits suited to intercropping.

The identification of complementary varieties of winter wheat and field pea is crucial for the adoption of intercropping systems from local farmers.

The objective of this work was (i) to evaluate field pea and bread winter wheat varieties as sole crops and intercrops for the identification of the most promising and high-yielding mixtures in the specific environment based on grain yield, yield components, LER, AYL, GMA, and SMA; (ii) to identify which of these criteria could be further exploited for the detection of complementary cultivars and the creation of successful mixtures; and (iii) to propose the key traits that should be used as targets in breeding programs aimed to produce new pea and wheat genetic material suitable for intercropping.

2. Materials and Methods

2.1. Experimental Site

The experiment was conducted for two successive growing seasons (2018–2019 and 2019–2020) at the University Farm of Aristotle University of Thessaloniki at the area of Thermi (40°32′9″ N 22°59′18″ E, 0 m). The soil characteristics are given in Table 1 and the soil type was a clay loam. The soil contained all the essential nutrients for plant growth in adequate concentrations and there was no need for fertilization.

Table 1. Soil characteristics of the experimental field at the University Farm where the experiments were conducted.

Characteristics	Soil Depth (0–30 cm)
Sand (g kg^{-1})	30
Silt (g kg^{-1})	35
Clay (g kg^{-1})	35
Soil texture	Clay loam
pH (1:1 H_2O)	8.1
EC (dS m^{-1})	0.621
Organic matter (g kg^{-1})	10
Total N (Kjeldahl) (g/100g)	1
P (Olsen mg kg^{-1})	11
$CaCO_3$ (g 100g^{-1})	5
Ca++ (g kg^{-1})	6.4
Mg++ (g kg^{-1})	7.66
K (exchangeable mg kg^{-1})	51.00
Fe++ (mg kg^{-1})	9.7
Zn++ (mg kg^{-1})	1.1
Mn++ (mg kg^{-1})	14
Cu++ (mg kg^{-1})	3
B (mg kg^{-1})	1.2

Source: Land Reclamation Department, Soil and Water Resources Institute, Hellenic Agricultural Organisation "DEMETER", Sindos, Greece.

The weather conditions, provided in Figure 1, were recorded daily for the two growing seasons using an automatic weather station close to the experimental site and were reported as mean monthly data.

2.2. Genotypes Used in the Study

We tested different cultivars from two species of wheat and pea, which are important crops for food and also feed, and have potential to be adapted by farmers for intercropping systems. The selected cultivars cover different characteristics such as plant height (tall vs short), maturity (early, mid-early, and mid-late), and grain size (low thousand kernel weight vs high), which comprised different ideotypes. Six wheat and two pea cultivars as well as mixtures of each wheat cultivar with each pea cultivar were used in this study. The wheat cultivars that were used were Yecora E, Elissavet, Vergina, Nestos, Flamenko, and Mavragani (a local landrace with good adaptability), and the pea cultivars were Isard and Livioletta. The pea cultivar Isard is an afila type, while Livioletta is a leafy type with indeterminate growth. In addition, the wheat cultivars were selected because of the differences in plant height, flowering time, earliness, morphological traits (spike size), and grain yield. The genotypes were developed by different companies and also by national institutes. In particular, the wheat cultivars Yecora E, Elissavet, Vergina, and Nestos were developed by the National Institute of Cereals in Greece. Mavragani is a landrace that was evaluated by the same institute. Isard was developed by Agri Obtentions and Livioletta is a widely used cultivar in Europe.

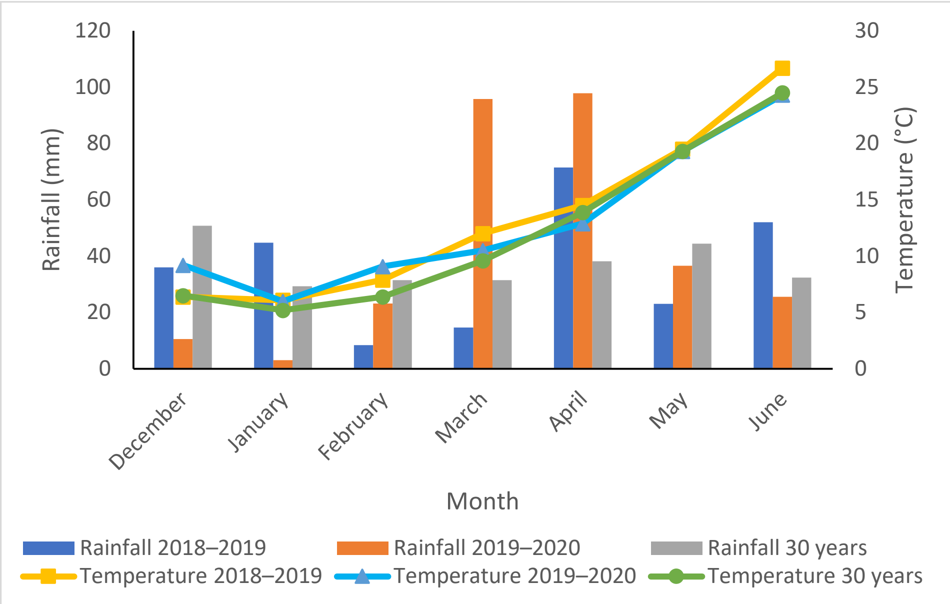


Figure 1. Main weather parameters (mean temperature and rainfall) for the two growing seasons (2018–2019 and 2019–2020) of experimentation at Thermi, Greece, and its comparison to the 30-year average. The weather data were recorded using an automatic weather station close to the experimental site.

2.3. Crop Management

Monocrop of pea and wheat cultivars, as well as mixtures of pea with each of the wheat, were sown on the first week of December in the two growing seasons. The seeding ratio was 75:25 (pea:wheat) based on seed weight. The seeding rates for the pea and wheat monocrops were 130 and 150 kg ha^{-1}, respectively, whereas the seeding rates for the intercrops were 98 and 38 kg ha^{-1} (pea–wheat) [16]. The seeds of both species were sown simultaneously in the same line and at a depth of 2–3 cm. The seeding ratio was selected as it was found from previous experiments in the area [29,33,34].

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 conventional and the soil was moldboard plowed, harrowed, and a cultivator was used. All crops were kept free of weeds by implementing hand hoeing, where necessary. No supplemental irrigation was applied and the experiments were carried out in rainfed conditions without any irrigation in both years.

The experimental design was a randomized complete block design (RCBD). The experiment consisted of three blocks and each block contained 20 treatments (8 monocrop and the 12 combinations of the pea and wheat cultivars). Every experimental plot was 4 m in length with five rows 25 cm apart, and the total size of each plot was 5 m^2. The plots were separated by a 1 m "buffer" zone.

2.4. Grain Yield Determination

All cultivars that were used matured in the same period in both years, and harvest took place at the full-maturity stage. In order to determine the grain yield, three central rows were harvested and the grains were received with a LD 350 laboratory thresher (Wintersteiger AG, Ried im Innkreis, Austria) in the first week of June in both years. In the intercropping treatments, the grains were separated with a grain separator and then weighed.

2.5. Grain Yield Components

The yield components (number of spikes per plant, number of pods per plant, number of grains per spike, number of grains per pod) were determined by measuring the number of spikes, pods, and grains from 10 plants per plot at harvest.

2.6. Land Equivalent Ratio (LER)

The advantage of intercropping and the effect of competition between the two species used in a mixture was calculated using the land equivalent ratio (LER). In particular, LER indicates the efficiency of intercropping for using the environmental resources compared with monocropping. The value of unity is considered the critical value for this index. When LER is greater than one, the intercropping favors the growth and yield of the inter-cropped species, whereas when LER is lower than one, the intercropping negatively affects the growth and yield of the species [27,28]. The LER was calculated as [27]:

$$LER = (LER_p + LER_w), \quad (1)$$

$$LER_p = (Y_{pi}/Y_p), \quad (2)$$

$$LER_w = (Y_{wi}/Y_w), \quad (3)$$

where Y_p and Y_w are the yields of pea and wheat, respectively, as monocrops and Y_{pi} and Y_{wi} are the yields of pea and wheat, respectively, as intercrops. Similarly, LER_p and LER_w are the estimation of partial LER for pea and wheat, respectively, and LER is the total LER for each mixture.

2.7. Actual Yield Loss (AYL)

The actual yield loss (AYL) index could further clarify the relationship between the co-cultivated species and give more information about the competition and the performance of each species in the mixture. The AYL index expresses the yield loss or gain of the intercrop compared to the pure stand [35]. Banik [30] proposed the calculation of the AYL index with the following formula:

$$AYL = (AYL_p + AYL_w), \quad (4)$$

$$AYL_p = [(Y_{pi}/Z_{pi})/(Y_p/Z_p)] - 1, \quad (5)$$

$$AYL_w = [(Y_{wi}/Z_{wi})/(Y_w/Z_w)] - 1, \quad (6)$$

where Y_p and Y_w are the yields of pea and wheat, respectively, as monocrops and Y_{pi} and Y_{wi} are the yields of pea and wheat, respectively, as intercrops. Additionally, Z is the sown proportion of pea and wheat as monocrops (Z_p and Z_w) and in mixtures (Z_{pi} and Z_{wi}). Furthermore, AYL is the total estimation for each mixture, while AYL_p and AYL_w are the index estimations for pea and wheat, respectively.

2.8. GMA and SMA Estimation

The GMA and SMA indices were estimated according to the methodologies proposed by Gizlice et al. [22] and Han et al. [21].

2.9. Statistical Analysis

The data for grain yield, yield components, LER, and AYL were analyzed with the analysis of variance (ANOVA) method combined over the two growing seasons. In each growing season, the experiment was based on the randomized compete block design (RCBD), consisting of three blocks and 20 treatments. The "protected" least significant difference (LSD) criterion was used for testing the differences between the treatment means. In all hypothesis-testing procedures, the significance level was predetermined at $a = 0.05$ ($p \leq 0.05$). All statistical analyses were accomplished with the IBM SPSS v23.0 statistical software.

3. Results

The two years showed great variability regarding the weather conditions, especially in rainfall distribution throughout the growing season and the mean monthly temperature during December (Figure 1). The results of the combined ANOVA over the years for yield components, grain yield, LER, and AYL showed (data not presented) that the environmental conditions (different growing seasons), the treatments, and the interaction "growing season × treatments" significantly affected most of the characteristics that were measured, explaining the observed variation at the field.

3.1. Grain Yield

Grain yield was significantly affected mainly by the treatment (different monocrops or mixtures) and the interaction of year x treatment. Furthermore, a great advantage of the wheat species is obvious in the second year of experimentation that could be attributed mainly to the different climatic conditions (Figure 1). During the first year of experimentation, the highest grain yield was found at the intercrops of Isard with Vergina, Mavragani, Flamenko, and Nestos (6.24, 6.18, 5.18, and 5.17 $t \cdot ha^{-1}$, respectively). The lowest values had the cultivars Nestos and Elissavet (2.04 and 2.7 $t \cdot ha^{-1}$, respectively). The second year, the high-yielding treatments included the mixture Isard–Mavragani (6.41 $t \cdot ha^{-1}$), Yecora E (5.44 $t \cdot ha^{-1}$), and Vergina (5.15 $t \cdot ha^{-1}$). On the other hand, the lowest grain yield was measured for Livioletta (0.78 $t \cdot ha^{-1}$), Livioletta–Elissavet (1.03 $t \cdot ha^{-1}$), Isard (1.11 $t \cdot ha^{-1}$), Livioletta–Vergina (1.15 $t \cdot ha^{-1}$), and Livioletta–Flamenko (1.69 $t \cdot ha^{-1}$). Finally, after estimating the mean grain yield for the two years of cultivation, the mixture Isard–Mavragani and Isard–Flamenko were superior and exhibited a stable performance, while all the treatments that included Livioletta (pure stand and mixtures), the intercrop Isard–Elissavet, and the monocrops Isard and Elissavet had the lowest grain yields of the experiment (Figure 2).

3.2. Yield Components

In order to better understand the interaction between the two species (pea and wheat) during intercropping and the effect on the most important yield components, the number of pods per plant in the pea cultivars and spikes per plant in the wheat cultivars were measured (Table 2). The number of grains per pod or per spike was also recorded (Table 3). In the first year, all of the combinations were clustered into two separated groups according to the statistical analysis. The most pods per plant were measured for Livioletta, Livioletta–Mavragani, and Isard (from 19.3 to 13.8 pods per plant), which were statistically significantly different from all of the other treatments, while the second group included the mixture of Isard–Flamenko (5.8) that had the lowest number of pods per plant and all of the other combinations. During the second growing season, there was no statistically significant difference in the number of pods per plant in the treatments.

Table 2. Number of spikes and pods per plant in the different intercropping treatments for the two growing seasons.

Treatments	2018–2019		2019–2020	
	Number of Spikes per Plant Wheat	Number of Pods per Plant Pea	Number of Spikes per Plant Wheat	Number of Pods per Plant Pea
Yecora E	30.7 abcd *		7.9 a	
Elissavet	23.7 cdef		8.0 a	
Vergina	38.5 a		10.6 a	
Nestos	18.6 f		7.2 a	

Table 2. *Cont.*

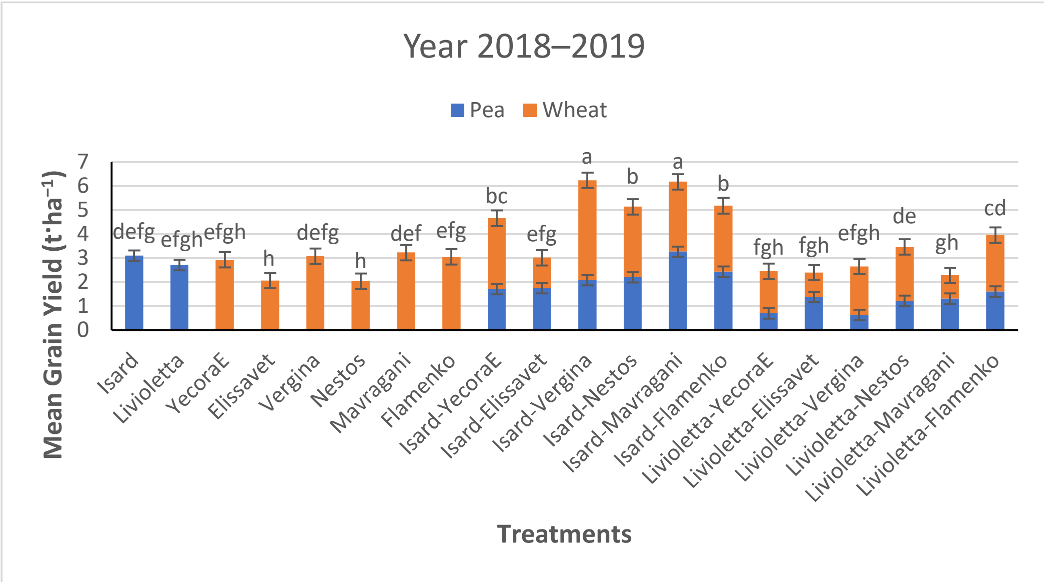
Treatments	2018–2019		2019–2020	
	Number of Spikes per Plant Wheat	Number of Pods per Plant Pea	Number of Spikes per Plant Wheat	Number of Pods per Plant Pea
Mavragani	30.7 abcd		7.8 a	
Flamenko	30.9 abcd		8.6 a	
Isard		13.8 abcd		10.0 a
Livioletta		19.3 a		8.4 a
Isard–Yecora E	32.3 abc	7.0 cde	9.7 a	6.2 a
Isard–Elissavet	18.6 f	9.7 bcde	10.1 a	7.1 a
Isard–Vergina	27.8 bcdef	6.5 de	11.2 a	8.3 a
Isard–Nestos	25.3 cdef	7.5 cde	10.1 a	5.6 a
Isard–Mavragani	20.2 ef	15.5 ab	8.1 a	4.6 a
Isard–Flamenko	21.0 def	5.8 e	11.6 a	5.7 a
Livioletta–Yecora E	37.8 ab	9.2 bcde	10.7 a	5.6 a
Livioletta–Elissavet	24.6 a	9.8 bcde	9.0 a	6.1 a
Livioletta–Vergina	25.1 cdef	7.3 cde	9.6 a	7.3 a
Livioletta–Nestos	31.4 abcd	10.0 bcde	9.1 a	7.5 a
Livioletta–Mavragani	29.5 abcde	14.1 abc	10.4 a	6.7 a
Livioletta–Flamenko	17.8 f	11.3 bcde	11.3 a	8.5 a
$LSD_{0.05}$ for number of spikes per plant			10.4	
$LSD_{0.05}$ for number of pods per plant			7.5	
Std. error for number of spikes per plant			2.603	
Std. error for number of pods per plant			1.859	

* Means followed by the same letter are not statistically significantly different, at significance level of 0.05, according to the LSD criterion.

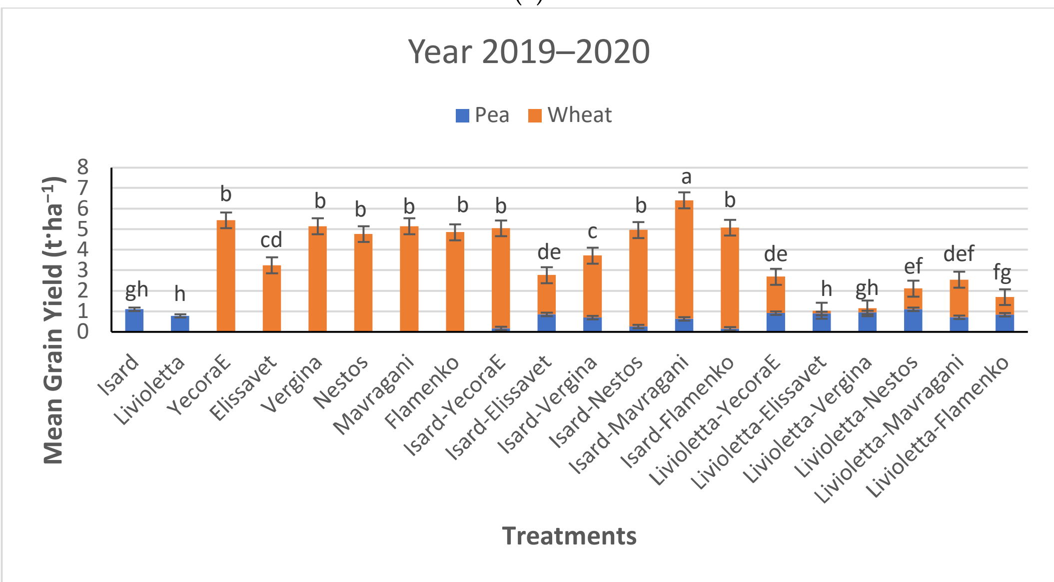
Table 3. Number of grains per spike and grains per pod in the different intercropping treatments during the two growing seasons.

Treatments	2018–2019		2019–2020	
	Number of Grains per Spike Wheat	Number of Grains per Pod Pea	Number of Grains per Spike Wheat	Number of Grains per Pod Pea
Yecora E	29.7 c *		29.7 bcde	
Elissavet	40.7 abc		32.2 abcde	
Vergina	30.0 c		38.9 ab	
Nestos	36.9 abc		23.3 de	
Mavragani	40.7 abc		29.4 bcde	
Flamenko	31.3 c		24.2 cde	
Isard		4.5 abcd		6.0 ab
Livioletta		5.7 a		5.6 abc
Isard–Yecora E	40.3 abc	3.3 abcd	26.9 cde	4.8 abc
Isard–Elissavet	35.8 abc	4.3 abcd	41.4 a	5.2 abc
Isard–Vergina	44.9 a	3.7 bcd	34.1 abcd	5.0 abc
Isard–Nestos	40.9 abc	3.0 d	29.9 abcde	3.9 c
Isard–Mavragani	43.6 ab	3.7 bcd	29.1 bcde	4.2 bc
Isard–Flamenko	39.0 abc	4.1 abcd	23.1 de	4.2 bc
Livioletta–Yecora E	37.2 abc	4.2 abcd	21.9 e	5.9 ab
Livioletta–Elissavet	40.0 abc	5.8 a	26.1 cde	5.2 abc
Livioletta–Vergina	45.9 a	4.4 abcd	29.9 abcde	5.7 abc
Livioletta–Nestos	39.4 abc	5.5 ab	28.7 bcde	5.7 abc
Livioletta–Mavragani	35.7 abc	5.0 abc	22.6 de	6.7 a
Livioletta–Flamenko	33.0 bc	4.7 abcd	34.9 abc	5.9 ab
$LSD_{0.05}$ for number of grains per spike			11.5	
$LSD_{0.05}$ for number of grains per pod			1.9	
Std. error for number of grains per spike			2.869	
Std. error for number of grains per pod			0.462	

* Means followed by the same letter are not statistically significantly different, at significance level of 0.05, according to the LSD criterion.



(**a**)



(**b**)

Figure 2. Grain yield of monocultures and intercrops in the two growing seasons: (**a**) 2018–2019; (**b**) 2019–2020 ($LSD_{0.05}$ = 1.27). Means followed by the same letter are not statistically significantly different, at significance level of 0.05, according to the LSD criterion.

Similar results were estimated for the number of spikes per plant for wheat cultivars in monocrops or in the mixtures (Table 2). In the first year, the wheat cultivars that produced the most spikes and did not differ were in the following treatments: Vergina, Livioletta–Yecora E, Isard–Yecora E, Livioletta–Nestos, Flamenko, Yecora E, Mavragani, and Livioletta–Mavragani (ranged from 29.5 to 38.5). Finally, during the second year, the number of spikes were, in some cases, almost four times fewer compared to the first year. Overall, the wheat cultivars did not differ in the number of spikes per plant.

The number of grains per pod and the number of grains per spike were also determined before harvest (Table 3). In the first growing season, the pea variety with the highest number of grains per pod was Livioletta at the mixture Livioletta–Elissavet (5.8), but did not differ significantly from most of the treatments except for the mixtures of Isard with the wheat cultivars Mavragani, Vergina, Yecora E, and Nestos. In the next growing season (2019–2020), the performance of pea cultivars was similar. The best combination for the specific trait was Livioletta–Mavragani (6.7), but according to the statistical analysis, most of the treatments did not have statistically significant differences apart from the following mixtures of Isard with the wheat cultivars Yecora E, Flamenko, Mavragani, and Nestos.

The performance of the wheat varieties based on the number of grains per spike was not stable between the years of experimentation (Table 3). More specifically, in the first growing season, the mixture with the most seeds per spike was Livioletta–Vergina (45.9), although it did not differ from most of the treatments with the exception of the mixture Livioletta–Flamenko and the monocrops Flamenko, Vergina, and Yecora E. In the second year, the treatments Isard–Elissavet (41.4), Vergina (38.9), Livioletta–Flamenko (34.9), Isard–Vergina (34.1), and Elissavet (32.2) included the wheat varieties with the most grains per spike.

3.3. Land Equivalent Ratio (LER)

The land equivalent ratio is usually estimated to depict the yield advantage of intercropping systems and indicates the land area required for pure stands in order to produce the same yield as intercropping (Table 4). In the first growing season, the highest LER values were estimated for five intercrops that included Isard and differ statistically significantly from the rest of the mixtures. More specifically, Isard–Nestos, Isard–Vergina, Isard–Mavragani, Isard–Flamenko, and Isard–Yecora E exhibited yield advantage with values 2.147, 2.017, 1.954, 1.683, and 1.557, respectively, indicating that Isard could be a pea variety appropriate for intercropping. The results of the second year did not agree with the first growing season, indicating the significant effect of environmental factors in the intercropping performance. So, according to the statistical analysis, all of the mixtures had an equal performance (LER values from 1.693 to 1.152) except for Isard–Yecora E (1.048).

Table 4. Land equivalent ratio of wheat (LER_w), pea (LER_p), and total land equivalent ratio (LER) of the different intercropping treatments.

Treatments	**2018–2019**			**2019–2020**		
	LERw	**LERp**	**Total**	**LERw**	**LERp**	**Total**
Isard–Yecora E	1.006	0.551	1.557 abcde *	0.897	0.151	1.048 b
Isard–Elissavet	0.614	0.564	1.178 def	0.588	0.776	1.364 ab
Isard–Vergina	1.344	0.673	2.017 ab	0.586	0.632	1.218 ab
Isard–Nestos	1.437	0.710	2.147 a	0.987	0.237	1.224 ab
Isard–Mavragani	0.901	1.053	1.954 abc	1.123	0.570	1.693 a
Isard–Flamenko	0.900	0.783	1.683 abcd	1.014	0.138	1.152 ab
Livioletta–Yecora E	0.598	0.259	0.857 f	0.326	1.168	1.494 ab
Livioletta–Elissavet	0.491	0.511	1.002 ef	0.041	1.143	1.184 ab
Livioletta–Vergina	0.654	0.233	0.887 f	0.040	1.208	1.248 ab
Livioletta–Nestos	1.098	0.451	1.549 bcde	0.212	1.405	1.617 ab
Livioletta–Mavragani	0.300	0.485	0.785 f	0.356	0.908	1.264 ab
Livioletta–Flamenko	0.770	0.594	1.364 cdef	0.175	1.076	1.251 ab
$LSD_{0.05}$ Total LER means				0.595		
Std. error for Total LER				0.150		

* Means followed by the same letter are not statistically significantly different, at significance level of 0.05, according to the LSD criterion.

For the estimation of LER, the partial LER values were initially estimated for each species of the mixture and added to estimate the total LER. In order to illustrate the inter-actions between the two species of the mixtures, a graphical representation was used [35–37]. In the top left quadrant are located all of the mixtures in which the pea suppresses the wheat (Figure 3). Most of the mixtures with Livioletta are allocated to this quadrant. In parallel, the bottom right quadrant includes the mixtures in which the wheat grain yield overcomes the pea yield. Three of the mixtures that include Isard (with Flamenko, Nestos, and Yecora E) are concentrated there. In the lower left quadrant, no intercrops are present, indicating that in all of the evaluated intercrops, there were no competitive effects that suppressed both species. Finally, the mixtures located in the top right quadrant exhibited complementarity and cooperation, leading to an advantage from intercropping compared to the pure stands. It is worth mentioning that three mixtures of Isard (with Vergina, Mavragani, and Elissavet) and the intercrop Livioletta–Nestos are gathered in this part of the graph, indicating a significant advantage of intercropping with these cultivars.

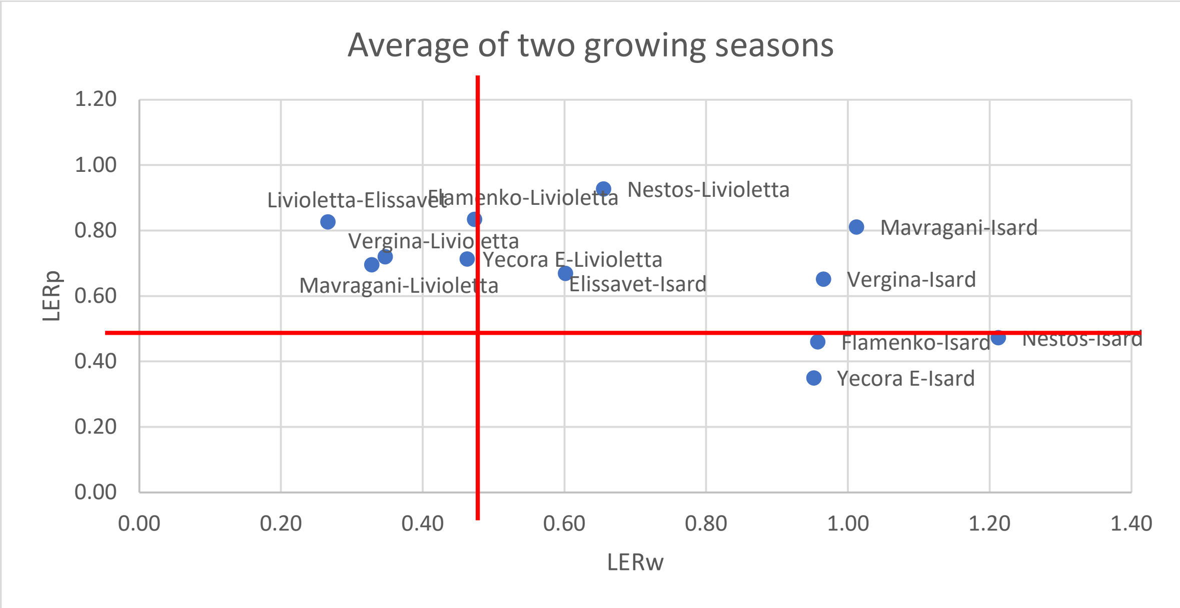


Figure 3. Graphical representation of the interaction between the two species based on the average partial LER values of pea (LERp) and wheat (LERw) of the intercropping systems under evaluation for two growing seasons.

3.4. Actual Yield Loss of Wheat (AYL)

The AYL index is usually estimated to depict the yield loss or gain of a mixture compared to the pure stand and the interaction of the included species (Table 5). In the first growing season, the highest AYL values were estimated for two intercrops that included Isard and differ statistically significantly from the rest of the mixtures. More specifically, Isard–Nestos and Isard–Vergina exhibited yield advantage with values of 4.695 and 4.276, respectively, indicating that Isard could be a pea variety appropriate for intercropping with both wheat cultivars. The results of the second year do not agree, probably due to significant environmental effects on the intercropping performance. So, according to the statistical analysis, four mixtures of Isard (with Mavragani, Nestos, Flamenko, and Yecora E) had better performance according to the AYL values.

3.5. GMA and SMA Estimation

According to the estimated GMA values depicted in Table 6, it is not possible to draw clear conclusions due to the variation that exists between the two growing seasons. Among the wheats, Mavragani, Flamenko, and Nestos are superior components of the mixtures when evaluating both their overall mean performance and for each growing season separately. In addition, Elissavet had the lowest and negative GMA value among the wheat cultivars during both years of experimentation.

The GMA estimations for the pea cultivars highlight Isard as a pea variety appropriate for intercropping, since it has the best or at least high GMA throughout both of the years. On the contrary, the GMA estimations for Livioletta indicate that this pea cultivar is not suitable for mixtures with wheat.

Table 5. Mean actual yield loss of wheat (AYLw), pea (AYLp), and total actual yield loss (AYL) of the different intercropping treatments.

Treatments	2018–2019			2019–2020		
	AYLw	AYLp	Total	AYLw	AYLp	Total
Isard–Yecora E	3.024	−0.265	2.759 c *	2.589	−0.799	1.790 abc
Isard–Elissavet	1.456	−0.248	1.208 de	1.352	0.035	1.387 bcd
Isard–Vergina	4.378	−0.102	4.276 ab	1.345	−0.157	1.187 bcde
Isard–Nestos	4.748	−0.054	4.695 a	2.948	−0.684	2.264 ab
Isard–Mavragani	2.603	0.404	3.007 bc	3.493	−0.239	3.253 a
Isard–Flamenko	2.600	0.045	2.645 cd	3.058	−0.816	2.241 ab
Livioletta–Yecora E	1.394	−0.656	0.739 e	0.305	0.558	0.864 bcde
Livioletta–Elissavet	0.963	−0.319	0.644 e	−0.837	0.524	−0.313 e
Livioletta–Vergina	1.615	−0.689	0.925 e	−0.841	0.611	−0.230 e
Livioletta–Nestos	3.392	−0.399	2.993 bc	−0.152	0.873	0.722 cde
Livioletta–Mavragani	0.198	−0.354	−0.156 e	0.425	0.211	0.636 cde
Livioletta–Flamenko	2.079	−0.208	1.871 cde	−0.298	0.435	0.137 de
$LSD_{0.05}$ Total AYL means				1.502		
Std. error for Total AYL				0.373		

* Means followed by the same letter are not statistically significantly different, at significance level of 0.05, according to the LSD criterion.

Table 6. General mixing ability (GMA) of wheat and pea varieties for the two growing seasons.

Species	Treatments	GMA		
		2018–2019	2019–2020	Total
Wheat	Yecora E	−0.41	0.60	0.10
	Elissavet	−1.26	−1.37	−1.32
	Vergina	0.47	−0.83	−0.18
	Nestos	0.33	0.27	0.30
	Mavragani	0.26	1.21	0.74
	Flamenko	0.60	0.12	0.36
Pea	Isard	1.10	1.39	1.25
	Livioletta	−1.10	−1.39	−1.25

The estimation of SMA for all of the mixtures revealed the great variation in the inter-crops' performance during the two growing seasons (Table 7) and confirmed the effect of environmental factors that was already evident from the analysis of variance. After examining the results from both years of experimentation, it is obvious that some conclusions about the mixtures can be drawn. More specifically, two superior combinations based on SMA that could be promising for increasing grain yield production are Livioletta–Elissavet and Isard–Mavragani. It is worth mentioning that the same varieties, when combined differently (Livioletta–Mavragani and Isard–Elissavet), also had the lowest SMA values. Finally, taking into consideration the SMA values from separate years, Isard–Vergina during the first growing season and Isard–Flamenko during the second year are also promising mixtures that can be adapted by farmers.

Table 7. Specific mixing ability (SMA) of wheat and pea varieties for the two growing seasons.

	Wheat					
	2018–2019					
Pea	Yecora E	Elissavet	Vergina	Nestos	Mavragani	Flamenko
Isard	0.00	−0.79	0.69	−0.26	0.85	−0.49
Livioletta	0.00	0.79	−0.69	0.26	−0.85	0.49

Table 7. *Cont.*

			Wheat			
			2019–2020			
Pea	Yecora E	Elissavet	Vergina	Nestos	Mavragani	Flamenko
Isard	−0.22	−0.53	−0.11	0.03	0.54	0.30
Livioletta	0.22	0.53	0.11	−0.03	−0.54	−0.30
			Total			
Pea	Yecora E	Elissavet	Vergina	Nestos	Mavragani	Flamenko
Isard	−0.11	−0.66	0.29	−0.12	0.69	−0.10
Livioletta	0.11	0.66	−0.29	0.12	−0.69	0.10

4. Discussion

The importance of varietal selection for the success of an intercropping system was reported previously. However, there are no cultivars available for the farmers to use in intercropping systems [38–42]. According to the results of the present study, the effect of the growing season was statistically significant for the yield components (number of pods or spikes per plant and number of grains per pod or spike) and the calculation of AYL. In the first year, the average rainfall and temperature were similar to the mean values of thirty years while, in comparison, the second growing season had high rainfall and high average temperature. Since climate, soil, abiotic and biotic stress, and crop management can variously affect the performance of a cultivar, it is obvious that it is not easy to predict whether a variety bred under monoculture could adapt successfully to intercropping conditions. Thus, the interaction between the varieties and the environment has been studied extensively; however, the reasons for why some cultivars respond better to intercropping conditions remain to be identified [41,43–45]. This is the reason that modelers currently studying intercropping have combined expertise from other sciences such as micro-meteorology, environmental physics, ecophysiology, ecology, and soil science. This is an attempt to better comprehend the processes and interactions between the different plant genotypes and also between plants and the ecosystem [46].

4.1. Grain Yield

Identifying the most promising mixtures for intercropping based on total grain yield is a difficult task. It is obvious that the highest water availability recorded in the second year boosted the growth of the wheat varieties. Subsequently, a higher grain yield for wheat species under pure stand was recorded, while in the mixtures, the yield percentage of wheat increased. It is well documented that water availability from double-ridge stage to anthesis affects the number of spikelets and kernels per spike and the fertility of surviving spikelets [47,48], thus having an impact on grain yield. Despite the different environmental conditions during the two growing seasons, the mixture Isard–Mavragani had the best performance.

The yield variability of peas could be attributed to abiotic (drought, high temperature) and biotic stress (weeds, insects, diseases) that could affect the crop development and productivity [49,50]. Furthermore, the pea cultivar that had the best performance as a biblend component (Isard) is leafless. It is extensively documented that the differences in plant architecture could influence the interspecific competition and the efficient exploitation of the environmental resources [2,5].

4.2. Yield Components

Based on the results from the first season, a high pod number was measured in the pea monocultures, which was expected, but also in mixtures of Isard and Livioletta with Mavragani, suggesting that Mavragani (a local landrace) could be a more appropriate wheat variety for intercropping with pea under local conditions. Wheat landraces are valuable, flexible, genetically dynamic, and diverse sources to broaden the genetic base of cultivated wheat and to develop new varieties with adaptations under a wide range of low-input and farming systems [51–53]. On the other hand, the climatic conditions of the second season, which were not representative according to the 30-year average, affected the number of pods diversely and no statistically significant difference was identified among any of the treatments.

Accordingly, most wheat monocrops and also the mixtures of Livioletta–Yecora E, Isard–Yecora E, Livioletta–Nestos, and Livioletta–Mavragani exhibited a high number of spikes per plant the first year of experimentation. In the second season, a great reduction in tillering was observed for all wheat varieties, which could be attributed to the higher than usual mean temperature recorded during the first stages of the crop development (December, season 2019–2020). According to Harrison et al. [54], an elevated temperature at the early stages hastens crop development and reduces the tillering phase, resulting in a decreased number of tillers.

The number of seeds per pod was mainly affected by the different genotypes and less by the cropping system for both years, since most of the intercrops with Isard had the lowest number. Similar results were presented by Monti et al. [55] and further supported by Osumi et al. [56], who found that legumes with fewer ovules per pod (such as pea) decrease the fruit set as a response to the shading conditions caused by intercropping.

Finally, significant variation was observed in the number of grains per spike for the seasons of experimentation. For this specific trait, the results from the analysis of variance indicated that the effect of year and the interaction of year with the treatment was significant, suggesting that the climate variability makes it difficult to draw safe conclusions. Giunta et al. [48] and Zhong-hu and Rajaram [57] also argued that grains per spike was a yield component very responsive to high temperature.

In trying to interpret the data, wheat appears to be the dominant crop and affects the grain yield of the mixture. In fact, Vergina, Elissavet, Mavragani, and Yecora E could be promising genetic material for intercropping. Of course, it must be pointed out that their combinations with Livioletta, a leafy cultivar with indeterminate growth, negatively affected the total grain yield with these wheat varieties. A similar pattern was recorded in pea–barley mixtures where cereal was also the dominant component, since indeterminate pea cultivars can climb with the help of the cereal and compete for light [31,49,58].

4.3. Land Equivalent Ratio (LER)

The calculated values for LER indicated that all of the combinations had a yield advantage over their respective monocrops, apart from the intercrops of Livioletta–Vergina, Livioletta–Yecora E, and Livioletta–Mavragani during the first growing season. However, the impact of the environmental factors on the early growth stages of bread wheat affected the performance of cereals the second year. Furthermore, the estimation of partial and total LER indicates that Isard is a promising pea variety for intercropping that does not suppress, in most cases, the wheat grain yield (with Vergina, Mavragani, and Elissavet).

The estimation of partial LER for pea and wheat and the total LER values confirmed the previous findings. Depending on the growing season, the best mixtures compared to their respective monocrops that exhibit stable performance are Isard–Mavragani and Livioletta–Nestos.

4.4. Actual Yield Loss (AYL)

Actual yield loss is another index used in intercropping systems to describe the advantages and the disadvantages of the different mixtures [30]. Moreover, AYL can provide more accurate information about the intra- and interspecific competition and behavior of the different crop species and cultivars that are used in an intercropping system [35]. The results from the present study showed that wheat had positive values, especially during the first growing season, and in most treatments during the second growing season compared with pea, indicating that wheat was an advantage of intercropping. The AYL_{total} values were different in the different cultivars and combinations, indicating differences between the cultivars that were used and also in their response to intercropping systems. Similar differences in AYL were reported in other studies where species with bigger root systems, high stature, and better adaptability to dry land conditions gave higher values of AYL [59]. However, the effect of different cultivars was not determined in AYL and the data from the present study indicate that it is an important index that can be used to evaluate the different intercropping systems.

4.5. GMA and SMA Estimation

GMA estimation also highlights Isard as promising variety for intercropping. Yecora E and Nestos could be also suitable under specific conditions, although further experimentation is necessary for drawing safe conclusions. The SMA values of the mixtures were not stable over the years. However, the best mixtures, based on the calculations, were Livioletta–Elissavet and Isard–Mavragani. The presence of significant interactions between crop system and environment indicated that the combinations responded differently in variable environments. According to Reinprecht et al. [60], the identification and selection of the most superior intercrops should be performed by exploiting various methodologies based on the intercrops' performance (trait-based) or index- or diallel-based selection. Other researchers recommend the early generation yield evaluation of the mixtures while incorporating the farmers' own management into the selection process, making the whole procedure feasible and efficient [40].

5. Conclusions

The proper selection of pea and wheat cultivars for intercropping is very important as it can affect the final grain yield and, consequently, the economic income of farmers. From the present study, it is obvious that environmental variables (climate and soil, biotic and abiotic stresses) have a considerable effect, which clearly has a decisive influence on the success of a specific intercropping system. The best combination adapted to local intercropping conditions was Isard–Mavragani, because it showed complementarity and cooperation and maintained high grain yield. This finding is also supported by the LER, AYL, GMA, and SMA results. Other promising mixtures based on total grain yield are Isard–Flamenko and Isard–Nestos, although further experimentation is necessary to confirm these results. Overall, these indices could also assist in combination with total grain yield and yield components in the identification of superior genotypes and the creation of new ones appropriate for intercropping systems.

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