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Land and Water Productivity in Intercropped Systems of Walnut—Buckwheat and Walnut–Barley: A Case Study

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Abstract: Intercropping arable crops in orchards is a sustainable land use for intensifying agricultural production, under the condition of plants' complementarity in sharing resources. This study investigated the aspects of water use and yields in intercropped systems of walnut and crops. To assess possible temporal complementarity between crops and trees, a summer crop—buckwheat—and a winter crop—barley—were intercropped in walnut orchards. The land and water productivity were studied under two designs: in an older, denser orchard and a younger one, with wider tree spacing. The results showed a reduction in yields and water productivity (WP) of intercrops due to the competition with walnut trees, with the exception of buckwheat in the younger orchard, where this summer crop surprisingly achieved the highest yield and WP. Nevertheless, in the system with mature fruiting trees, intercropping with winter barley was 53% more productive per unit of land and 83% more water-productive than growing walnut and barley separately but also 48% more land-productive and 70% more water-productive than the walnut–buckwheat system. Our results indicate positive effects of trees on microclimates but also emphasize the importance of species selection and systems design on the overall productivity of intercropped systems.

Keywords: agroforestry; intercropped orchard; walnut; water productivity; water equivalent ratio; land equivalent ratio

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1. Introduction

In recent decades, it has become apparent that climate change could be a significant threat to agricultural production, especially in semi-arid and arid areas suffering from drought. The climate assessment in Croatia, conducted by Perčec Tadić et al. [1], shows that the prevailing precipitation deficit occurs during the warm season. Regarding the Pannonian region, where most of the arable land is, a precipitation deficit occurs on a monthly basis. It is most pronounced in the region's eastern part from April to September. The authors classified this area as moderately vulnerable to drought, with its generally not irrigated arable land being the most sensitive.

Agroforestry systems, characterized by the addition of trees to agroecosystems, have a great potential for climate change mitigation, as well as providing better adaptation of food production systems to the changing climate conditions [2]. The addition of trees on arable land modifies the microclimate of the cultivated area, primarily by influencing radiation flux, reducing air temperature and wind strength, which increases relative air humidity. These changes can reduce evapotranspiration and improve the system's water utilization. Regardless of the positive effects of trees on microclimate conditions, there is always uncertainty about the productivity and profitability of understory crops, as their yields depend on many factors. Primarily, crop yields are determined by climate and soil properties. However, tree species, age, density, and management significantly affect the amount of shade and competition for belowground resources, so different species combinations in these systems give very different outcomes [3]. Although the reduction in crop yields in an intercropped system with trees is expected and recorded, studies showed that with a proper system design and species selection, competition could be reduced to the level where the crop in the intercropped system gives the same yields as a crop in monoculture [4], if not higher [5,6]. Despite low relative crop yields, these systems often have higher productivity [7–9], which may be the outcome of increased water availability [10].

Investigating intercropped systems of black walnut–maize and red oak–maize, Jose et al. [11] found that water competition with tree roots and not shading was the main limiting factor for maize productivity. Many others also argue the importance of water competition/complementarity in intercropped systems as crucial for system productivity [11–14]. Depending on soil hydrological characteristics, tree and crop species and their root distribution, seasonal requirements, and the level of competitiveness, tree–crop interactions can vary significantly. Nevertheless, when soil water is scarce, trees can 'prefer' to uptake water from deeper soil layers, reducing competition with crops in the upper layers and allowing for complimentary water use in the system [15]. Such complementarity was observed between Populus trees and corn and apple trees and corn, where corn extracted water from 0–60 cm, and primary water sources for trees were below 60 cm of soil depth [16,17]. Similarly, Bai et al. [8] found that in intercropped systems with apricot, crops extracted the water not used by apricot trees from the upper layers of the soil, resulting in a water use advantage of 39%, 51%, and 34% for intercropped systems with peanuts, millet, and sweet potatoes, respectively, in comparison to the monoculture systems.

Land and water use advantages in intercropped systems can be expressed using indices of LER—Land Equivalent Ratio—and WER—Water Equivalent Ratio. If LER > 1 and WER > 1, the intercropped system is more productive per unit of land and water, i.e., producing the same yield in sole systems would require extra land and water.

A more recent interest of arable farmers in switching to fruit growing provides a good opportunity for introducing intercropped orchard systems as a way of intensifying production and gaining a steady flow of income while trees become mature enough to produce yield. The aim of our research was to investigate the land and water productivity of walnut orchards (*Juglans regia* L.) intercropped with buckwheat (*Fagopyrum esculentum* Moench.)—a summer crop with high water needs—and winter barley (*Hordeum vulgare* L.)—a crop with relatively low water needs. Intercrops yields and water productivity were compared with monoculture systems, as well as between older and younger orchard systems.

2. Materials and Methods

2.1. Field Experiments and Systems Description

Field experiments were conducted during 2019 and 2020 on two locations in eastern Croatia: Đakovo (45°18′24.09″ N, 18°26′20.5″ E) and Ivankovo (45°18′53.71″ N, 18°40′21.49″ E). Đakovo's site elevation is 111 m above sea level, and the Ivankovo site is 88 m above sea level. Soil type on both sites is luvisol pseudogley on loess, and the effective soil depth is 1500 mm. Soil preparation before buckwheat and barley sowing was uniform on both sites and for both monoculture and intercropped systems. It consisted of plowing up to 30 cm and soil leveling. Soil physical and chemical properties for different years, sites, and systems are given in Tables 1 and 2, respectively.

Table 1. Soil physical properties.

Location	Depth (cm)	Particle Size Distribution (%) Sand	Clay	Silt	Texture Class	Bulk Density (g cm^{-3})
Đakovo	0–40	2.95	25.9	71.15	silt loam	1.51
	40–60	2.72	28.07	69.21	silty clay loam	1.56
	60–125	2.57	27.72	69.71	silt loam	1.56
Ivankovo	0–40	3.7	17.96	78.34	silt loam	1.54
	40–60	2.73	29.12	68.15	silt loam	1.6
	60–110	2.02	34.02	63.96	silty clay loam	1.6
	110–140	2.43	29.95	67.62	silt loam	1.6

Table 2. Soil chemical properties.

Year	Soil Properties	Đakovo Monoculture	Đakovo Intercropped Orchard	Đakovo Orchard	Ivankovo Monoculture	Ivankovo Intercropped Orchard	Ivankovo Orchard
2019 Buckwheat	pH(H_20)	5.6 ^{b}	6.2 ^{b}	6.0 ^{b}	6.0 ^{b}	7.3 ^{a}	5.9 ^{b}
	AL-P_2O_5 mg/100 g	10.3 ^{bc}	7.0 ^{bc}	5.9 ^{c}	13.6 ^{ab}	17.7 ^{a}	19.1 ^{a}
	AL-K_2O mg/100 g	12.4 ^{c}	13.0 ^{c}	14.4 ^{c}	16.5 ^{bc}	19.1 ^{b}	24.9 ^{a}
	SOM%	1.6 ^{a}	1.6 ^{a}	1.6 ^{a}	1.7 ^{a}	1.6 ^{a}	1.5 ^{a}
2020 Barley	pH(H_20)	5.6 ^{c}	5.9 ^{bc}	6.3 ^{b}	6.2 ^{b}	6.9 ^{a}	5.7 ^{c}
	AL-P_2O_5 mg/100 g	9.5 ^{bc}	6.9 ^{c}	9.6 ^{bc}	14.9 ^{a}	14.5 ^{a}	12.1 ^{ab}
	AL-K_2O mg/100 g	11.8 ^{c}	14.6 ^{bc}	18.5 ^{a}	18.5 ^{a}	19.5 ^{a}	17.6 ^{ab}
	SOM%	1.6 ^{c}	2.0 ^{ab}	2.2 ^{a}	1.4 ^{c}	1.6 ^{c}	1.7 ^{bc}

Means denoted by different letters (^{a}, ^{b} and ^{c}) indicate significant differences between systems (p < 0.05; Tukey's test).

Each location consisted of three plots: (a) control plot of monoculture crop; (b) sole walnut orchard; (c) intercropped walnut orchard. Tree rows in both locations were oriented north–south.

In Đakovo, the walnut orchard was 12 years old with 8 m alleys between grafted walnut trees. Within intercropped orchard, crops were sown in strips of 6 m in width, giving a crop area of 0.75. Buckwheat was grown during the summer of 2019. It was sown on 27 May and harvested on 3 September. Barley was sown on 28 October of the same year and harvested on 30 June 2020. Walnut orchard in Ivankovo was 5 years old with a distance between tree rows of 10 m and crop strips width of 8 m, resulting in a crop area of 0.8. Buckwheat was sown on 10 June and harvested on 17 September 2019. Barley was then sown on 3 November and harvested on 10 July. Neither fertilization nor irrigation was applied to any of the experimental plots.

2.2. Yields Determination

Crop yields were determined by harvesting plants from a 1 m^2 area on 16 random points for each system, separating and weighing the grain, and calculating the grain weight per 1 ha area to obtain total yields in kg ha^{-1}. To account for the bare, unsown area in intercropped orchards (tree row strip), determined crop yields (per crop area) were multiplied by 0.75 (Đakovo) and 0.8 (Ivankovo) to obtain yields per total area. In Đakovo, walnut yields were determined by collecting fruit from each walnut system and weighing it: in 2019 as a kernel in a shell and in 2020 as a nut in a green husk. Since the orchard in Ivankovo is young and has not started yielding significantly, the fruit yield was not determined there.

2.3. Soil Water Content

Soil volumetric water content throughout growing seasons was derived from soil water potential data. The matric potential of soil water was recorded continually using Watermark sensors (Environmental Measuring Systems s.r.o., Brno, Czech Republic) on each site. Additional sensors were carefully placed in the soil samples ring from each site for calibration. These were then soaked in water until fully saturated, left for a few days, and then removed from the water onto a dry tray. The measurements of water matric potential were recorded from sensors, and the sample rings were weighted every few hours until completely dry. From determined gravimetric water content and water potential readings, regression equations were obtained, allowing the exploration of volumetric water content for each site throughout growing seasons. However, due to technical issues with sensors on experimental plots in fall 2019, water content data during barley vegetation are missing. In order to calculate water use during barley vegetation, soil water content at sowing and harvest was then determined manually by collecting soil ring samples and determining gravimetric water content. The soil water measurements were recorded for 30, 60, and 90 cm of soil depth, and the average values were used to interpret the results. Although these may not represent total water use in intercropped systems with trees, they probably represent a significant part of the water available and used by crops and trees.

2.4. Hydrothermal Coefficient of Water Protection

Temperature and precipitation data were obtained using Vantage Pro2 meteorological stations (Davis Instruments Corporation, Hayward, CA, USA) placed in both experimental locations. The meteorological station measured hourly data, which was then summed for the total daily amount of precipitation and averaged for the daily average temperature (Figure 1).

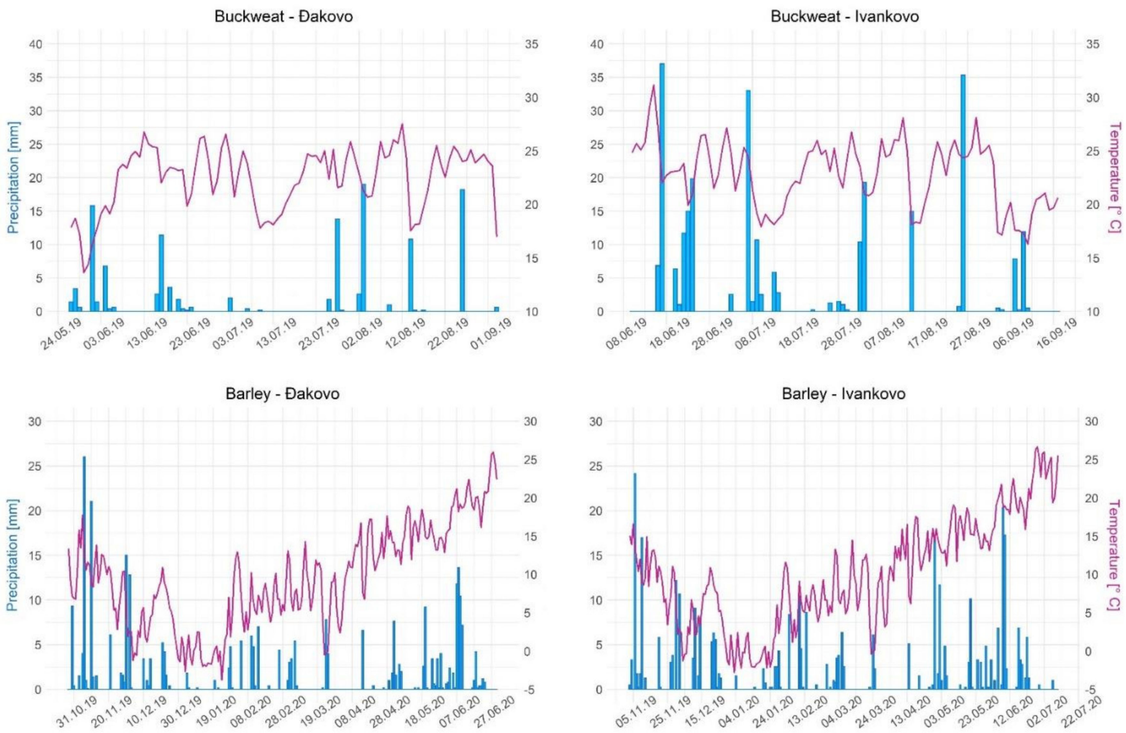

Figure 1. Measured temperature and precipitation during buckwheat and barley vegetation.

To describe the comprehensive effect of temperature and humidity conditions, the hydrothermal coefficient (K) was calculated monthly during crops vegetation; K = 10 * monthly sum of rainfall [mm]/number of days * average daily air temperature in a month [°C].

Interpretation of the hydrothermal coefficient according to Selyaninov [18]:

1. $K > 1.5$: excessive humidity for most plants;
2. $1 < K < 1.5$: humidity sufficient for most plants;
3. $0.5 < K < 1.0$: insufficient humidity for most plants;
4. $K < 0.5$: drought.

2.5. Water Productivity Determination

Soil water content and precipitation data were used in the water balance equation [19] for calculating growing season evapotranspiration (ET_C, mm), which represents actual water use (WU, mm) of the studied systems:

$$WU = P + S_1 - S_2$$

where P is the amount of rainfall (mm) during the crop growing season, S_1 is the water content (mm) within 0–100 cm soil depth at crop sowing, and S_2 is the water content at crop harvest. Water runoff and capillary rise have not been considered because experimental fields are quite flat, and the water table is low (below 10 m). Due to the presence of a poorly permeable Btg subsoil horizon with higher clay content on both sites, downward drainage is negligible and has therefore been excluded from the water balance equation. Since crop and walnut roots overlap in intercropped systems, water use was not partitioned for each plant species but for the system as a whole. It was determined by averaging WU measurements from the middle of an intercropped alley and within tree rows.

Water productivity (WP, kg ha^{-1} mm^{-1}) was calculated as the ratio of the yield and the previously defined water use:

$$WP = Y/WU$$

where Y is crop or fruit yield (kg ha^{-1}), and WU is the actual water use per unit area of a system (mm).

2.6. Land and Water Equivalent Ratios

The land equivalent ratio (LER) was estimated from crop yields and walnut fruit yields to characterize land use efficiency. The LER can be defined as the ratio of the area under monoculture production to the area under intercropping needed to give equal yields at the same management level [20]. It is calculated as the ratio of tree yield from intercropped system to the tree monoculture yield, plus the ratio of crop yield from intercropped system to the crop monoculture yield [21]. In other words, it is the sum of relative walnut and crop yields:

$$LER = pLER_W + pLER_C = Y_{int,W}/Y_{mono,W} + Y_{int,C}/Y_{mono,C}$$

where $pLER_W$ and $pLER_C$ are so-called partial LERs of walnut and crop, i.e., relative yields of species in the intercropped system. $Y_{int,W}$ and $Y_{int,C}$ are yields of walnut and crop in the intercropped system, respectively, and $Y_{mono,W}$ and $Y_{mono,C}$ are walnut and crop yields in monoculture plot, respectively. When LER ≤ 1, there is no agronomic advantage of intercropping over sole cropping, but when LER is >1, production in the intercropped system is higher than in the separate sole systems, meaning that producing the same yields in monoculture systems would require more land area.

To assess the water use advantage of the intercropped system, the water equivalent ratio (WER) was defined by analogy to LER. WER was calculated as the ratio of intercropped walnut WP to the walnut monoculture WP plus the ratio of crop WP in the intercropped system to the crop monoculture WP:

$$WER = pWER_W + pWER_C = WP_{int,W}/WP_{mono,W} + WP_{int,C}/WP_{monoC}$$

Similar to LER, WER values quantify the amount of water needed in monoculture plots for walnut and crops to achieve the same yield as produced with one unit of water in the intercropped system. WER > 1 indicates a water use advantage for the intercropped system, meaning that yields in the intercropped system are produced with less water than needed for the same yields in monoculture plots. Therefore, WER was used to determine whether water was used more efficiently in intercropping than in traditional sole cultivation [22]. If both LER > 1 and WER > 1, then the intercropped system requires less land and less water than monoculture cultivation.

Since walnuts in Ivankovo still have not produced significant fruit yield, LER and WER values were determined for the Đakovo site only.

2.7. Statistical Analysis

Statistical analysis of the obtained data was conducted in R software [23] using Analysis of variance (ANOVA) and Tukey's honestly significant difference (HSD) post hoc test. Non-parametric alternative tests were applied where appropriate—Welch's ANOVA in case of significant variance heterogeneity or/and unbalanced data, followed up by Games-Howell post hoc test. Differences between locations and systems were tested for soil chemical properties, yields, LERs, water productivity, and WERs. Regression analysis was used to check whether soil chemical properties influenced yield and water productivity. No significant correlations were found, so these results are not presented in detail.

3. Results

3.1. Yields and Land Equivalent Ratios

Unexpectedly, in Ivankovo, the intercropped buckwheat yield was higher than the monoculture buckwheat yield: 1985 and 1689 kg ha^{-1}, respectively (Figure 2a). This resulted in a high average $pLER_C$ of 1.17 (Table 3).

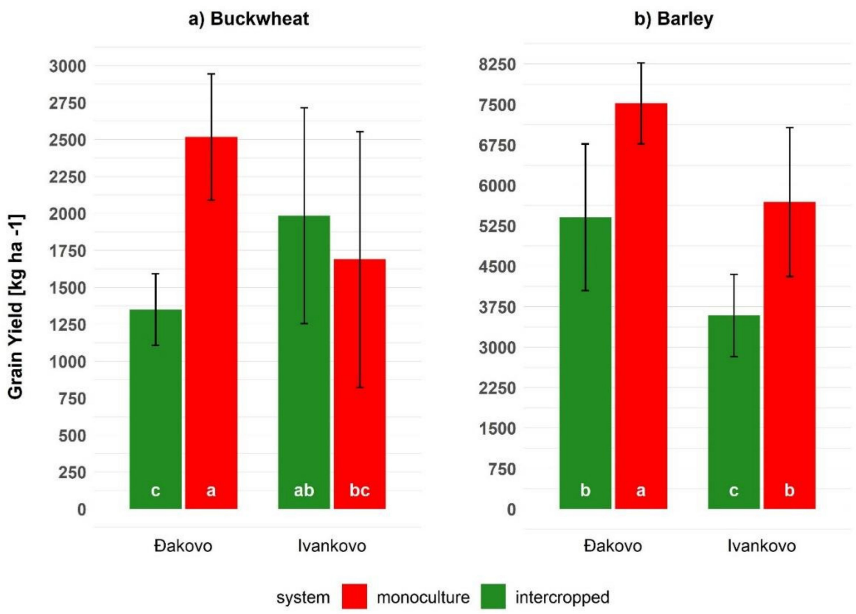

Figure 2. Grain yields of (**a**) buckwheat and (**b**) barley in monoculture and intercropped systems (per total area). Bars denoted by different letters (a, b and c) indicate significant differences between systems ($p < 0.05$; Tukey's test). Vertical bars represent standard deviation from the mean value.

Table 3. Land equivalent ratios.

Location	Crop	$pLER_C$	$pLER_W$	LER
Đakovo	Buckwheat	0.54 ± 0.09 [b]	0.51	1.05 ± 0.09 [b]
	Barley	0.72 ± 0.18 [b]	0.81	1.53 ± 0.18 [a]
Ivankovo	Buckwheat	1.17 ± 0.43 [a]	-	-
	Barley	0.63 ± 0.13 [b]	-	-

Means denoted by different letters ([a] and [b]) indicate significant differences between systems ($p < 0.05$; Tukey's test). $pLER_C$ (crops) differences were tested for both species together and LER for Đakovo between two years. The significance of the difference between walnut $pLER_W$ was not tested as there was only one data point for each system.

In Đakovo, the situation was the opposite—the monoculture had a significantly higher buckwheat yield than the intercropped system (2517 and 1349 kg ha^{-1}, respectively), and it was the highest observed buckwheat yield (Figure 2a). This resulted in a relatively low buckwheat $pLER_C$ of 0.54.

Walnut fruit yields in Đakovo showed significant differences between the first and second half of the orchard long before intercropping. The first half always had lower yields, and intercropping between its rows was a way of increasing the productivity of that part of the orchard. Correspondingly, 2019 was no exception—the intercropped part of the orchard produced only 51% of sole orchard fruit yield (378 and 746 kg ha^{-1}, respectively).

The partial crop and walnut LERs gave a total LER of 1.05, which means the intercropped system was, on average, 5% more productive in terms of land use efficiency than growing buckwheat and walnut separately (Table 3).

On the other hand, barley yielded significantly higher in monoculture in both locations: 7519 kg ha^{-1} in Đakovo and 5688 kg ha^{-1} in Ivankovo (Figure 2b). Furthermore, barley intercropped yield in Đakovo (5407 kg ha^{-1}) resulted in higher $pLER_C$ than in Ivankovo (3586 kg ha^{-1}): 0.72 and 0.63, respectively (Table 3).

Walnut yield in Đakovo in 2020 amounted to 2136 kg ha^{-1} in the intercropped orchard and 2625 kg ha^{-1} in the sole walnut stand, which gave higher a walnut $pLER_W$ (0.81) than the previous year. This led to a higher average LER of 1.53, meaning that the intercropping system of walnut and barley was 53% more productive per unit of land area than its respective monoculture systems and 48% more productive than the walnut–buckwheat system (Table 3).

3.2. Soil Water Content and Air Hydrothermal Conditions

During both years, Đakovo generally had more frequent and longer dry periods than Ivankovo, especially during buckwheat vegetation. There was no significant difference in air temperature between the locations. However, Ivankovo had more rain (263 mm during buckwheat vegetation and 352 mm during barley vegetation) than Đakovo (122 mm and 294 mm during buckwheat and barley vegetation, respectively) (Figure 1). This resulted in an overall higher hydrothermal coefficient for Ivankovo during both years (Figure 3).

In 2019, during buckwheat vegetation, the soil water content in monoculture systems did not differ significantly between the two locations. However, the differences were pronounced between systems in both locations. In Ivankovo, buckwheat in the intercropped system had higher water content through vegetation than buckwheat in the monoculture plot. Sole orchard also had lower soil water content than the intercropped orchard, especially during the second half of the summer (Figure 3b). On the other hand, in Đakovo, the soil water content in the intercropped system was lower than in the monoculture during the critical vegetation stage for buckwheat—flowering. In addition, the soil water content in the sole orchard was higher than in the intercropped orchard (Figure 3a).

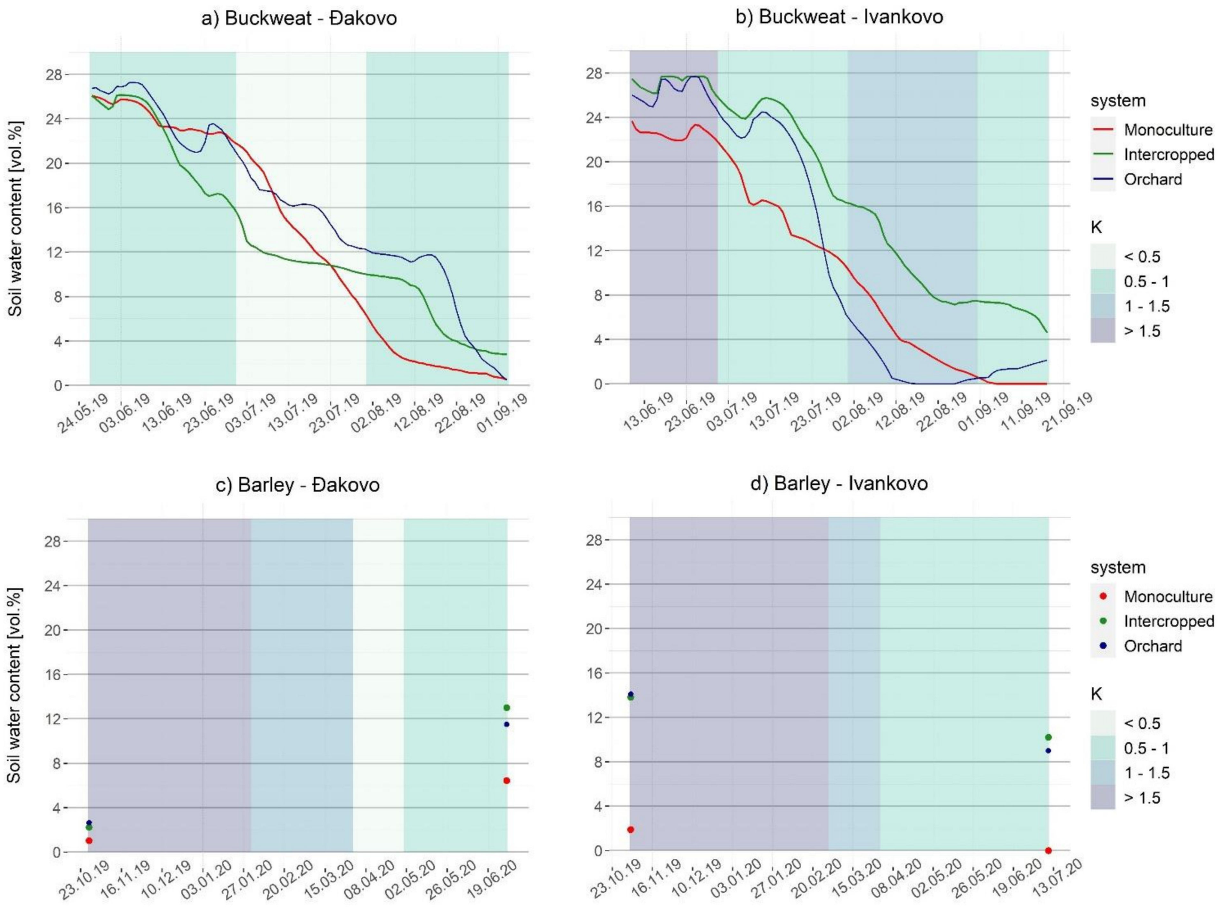

Figure 3. Soil water content and hydrothermal coefficient (K) during crops vegetation periods: (**a**) buckwheat in Đakovo, (**b**) buckwheat in Ivankovo, (**c**) barley in Đakovo, (**d**) barley in Ivankovo. Measurements during barley vegetation were taken at sowing and harvest.

Data on soil water content during barley vegetation were not recorded continuously. Nevertheless, the measurements at sowing and harvest showed higher water content in intercropped systems compared to monoculture barley plots. In both locations, sole walnut orchards initially had about the same amount of water as intercropped systems and slightly less at crop harvest (Figure 3c,d).

3.3. Water Productivity and Water Equivalent Ratios

During 2019 in both locations, the intercropped systems used less water (WU) than their respective monoculture systems, which indicates that intercropping reduced evapotranspiration (Figure 4a). However, since grain yield in Đakovo was significantly reduced, water productivity (WP) of intercropped buckwheat was also lower than monoculture buckwheat. The average $pWER_C$ amounted to 0.57. The same was observed for walnut WP—sole orchard walnuts were more productive per unit of water than intercropped trees. Nevertheless, this system was, on average, 12% more water-efficient (WER) than separate walnut and buckwheat (Table 4).

On the other hand, in Ivankovo, high buckwheat $pWER_C$ was consistent with $pLER_C$, and it showed that buckwheat in the intercropped system was more water-productive than monoculture buckwheat (Table 4).

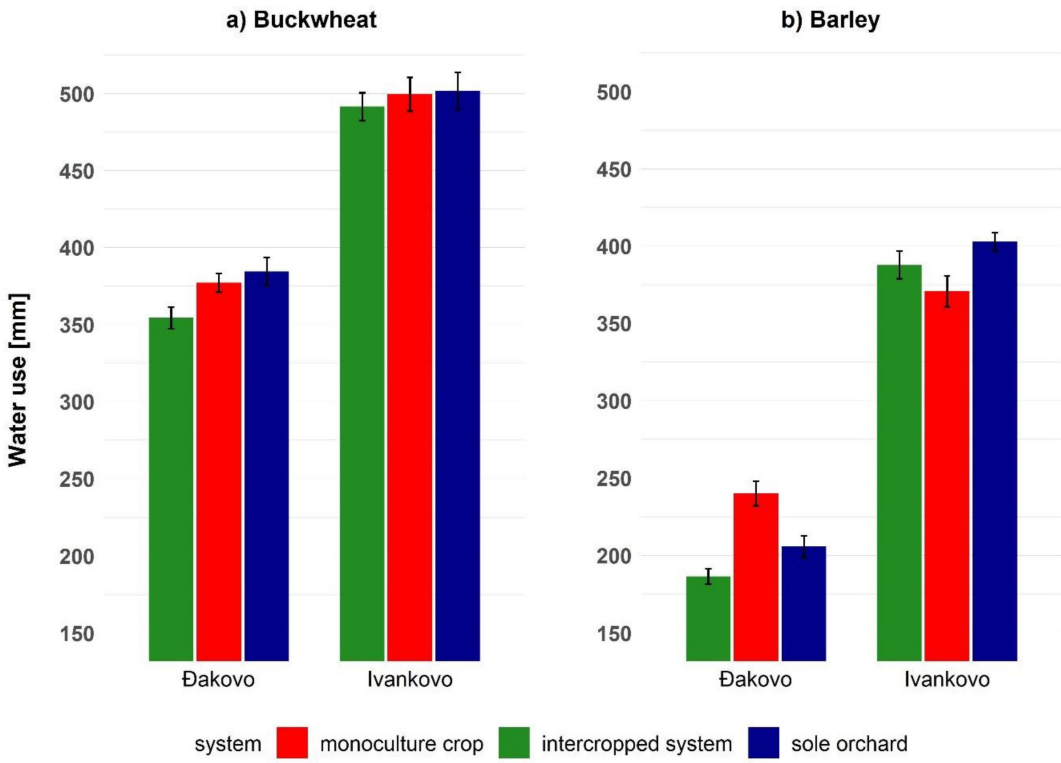

Figure 4. Water use, i.e., ET_C in monoculture crop systems, intercropped systems, and sole walnut orchards during crops vegetation periods: (**a**) buckwheat, (**b**) barley. Vertical bars represent standard deviation from the mean value.

Table 4. Water productivity and water equivalent ratios.

Year/Crop Species	Location	System	WP (kg ha^{-1} mm^{-1})	pWER	WER
2019 Buckwheat	Ivankovo	Monoculture crop	3.38 ± 1.73^{b}	1.19 ± 0.44^{a}	-
		Intercropped crop	4.04 ± 1.48^{b}		
	Đakovo	Monoculture crop	6.68 ± 1.13^{a}	0.57 ± 0.10^{b}	1.12 ± 0.10^{b}
		Intercropped crop	3.81 ± 0.68^{b}		
		Sole walnut	1.94	0.55	
		Intercropped walnut	1.07		
2020 Barley	Ivankovo	Monoculture crop	15.34 ± 3.73^{b}	0.60 ± 0.13^{b}	-
		Intercropped crop	9.25 ± 1.96^{c}		
	Đakovo	Monoculture crop	31.32 ± 3.13^{a}	0.93 ± 0.23^{a}	1.83 ± 0.23^{a}
		Intercropped crop	28.99 ± 7.30^{a}		
		Sole walnut	12.76	0.90	
		Intercropped walnut	11.45		

Means denoted by different letters ([a], [b] and [c]) indicate significant differences between systems ($p < 0.05$; Tukey's test). WP was tested for each species separately, $pWER_C$ for both species together, and WER for Đakovo between two years. The significance of the difference between walnut WP and $pWER_W$ was not tested as there was only one data point for each system.

Intercropping with barley was significantly more successful in Đakovo than Ivankovo. While barley in Ivankovo achieved a $pWER_C$ of 0.60, in Đakovo, it amounted to a high 0.93, on average (Table 4). Furthermore, since the intercropped system in Đakovo used less water than the sole orchard (Figure 4b), and fruit yield was not significantly reduced, walnut trees also achieved high $pWER_W$. This led to the intercropped system with walnuts and barley being highly efficient in water utilization, showing that sole systems would need, on average, 83% more water to achieve the same yields as in the intercropped system

(Table 4). Consistently with LER, this system was also more water-efficient (WER) than walnut–buckwheat intercropped orchard by 70%.

4. Discussion

Our previous research [24] showed that intercropping walnut orchards could be a profitable transition solution for arable farmers aiming to switch to walnut fruit production. In addition, there are additional income opportunities for fruit growers from intercropping already established orchards. However, fruit growers' higher inputs and labor needed to be adopted pose a great risk under the uncertainty in the productivity of different crops influenced by mature walnut trees. Our study aimed to investigate environmental aspects of such systems, i.e., how productive and water-efficient can buckwheat (summer crop) and barley (winter crop) be under an older walnut orchard with a narrower alley, in contrast to a younger one, with wider crop alleys.

We observed great differences in regard to crop species and tree age/density. Namely, with respect to site-specific monoculture systems, intercropped buckwheat seemed to perform significantly better in the younger orchard and barley in the older one in terms of both yield and water productivity.

The walnut–buckwheat system in Đakovo achieved an average LER of 1.05 and a WER of 1.12. However, if we account for the deviations from these mean values, it is questionable if this system could be more productive per units of land and water than growing buckwheat and walnuts separately. Walnut trees in the intercropped system produced only 51% of sole orchard fruit yield; however, this part of the orchard always had lower yields, even before introducing intercrops, so it is not possible to ascribe a definite buckwheat effect to these observations. During the buckwheat vegetation, arid hydrothermal conditions were observed in Đakovo. Some studies suggest that shading by trees can mitigate the adverse effects of drought by reducing heat stress [25–27], retaining the water from evaporation and preserving more water for plant transpiration [28]. Even though the intercropped system probably did lower the evaporation, our results suggest that this effect was negligible as buckwheat's high water demands, especially during the seedling stage and flowering, were not met in the intercropped system where competition with walnuts was too intense. Water stress during this period has a high impact on lowering the number of flowers and, consequently, the number of seeds and total yield per unit area [29]. In addition, radiation transmittance reduced by large walnut canopies probably caused light stress and had a negative effect on buckwheat yield [12].

Contrary, in Ivankovo, where walnut trees are spaced widely and its smaller canopies do not overcast a significant shading on the understory, intercropped buckwheat achieved higher yield and water productivity than in the monoculture plot. Generally, Ivankovo had more favorable climate conditions during buckwheat vegetation than Đakovo and competition between trees and crops may not be significant if water is not scarce [15,30]. Our results show that young walnut trees did not interfere with buckwheat's water consumption, as opposed to observations in Đakovo. In addition, the higher water content in the intercropped orchard, as opposed to monoculture plot and sole orchard, implies that buckwheat and walnut trees efficiently shared the water that would otherwise evaporate from the soil surface. Unexpectedly high buckwheat yield in the intercropped system could not be explained by differences in soil properties between observed systems, and it is difficult to describe the mechanism behind complementary interactions in this system without detailed research of belowground processes and root distribution. Furthermore, even though it is possible that buckwheat was the dominant species in this system, it was not possible to quantify its impact on walnut yield and water productivity since the young walnut orchard has not produced any yield yet.

Due to both high crop and walnut relative yields, the intercropped system of walnut and barley in Đakovo achieved high LER and WER. Our results showed that this system was, on average, 53% more land-productive and 83% more water-productive than separate monoculture systems, and it was also 47% more productive per unit of land and 71%

more water-productive than the walnut–buckwheat system. As previously mentioned, the intercropped part of the orchard always gave significantly lower fruit yields in previous years, even before introducing arable intercrops. However, in 2020, the difference was not that significant. Improved walnut pLERW (0.81) and pWERW (0.90) show that either subtle changes in soil properties of the intercropped orchard are positively affecting walnut productivity or there may be some underlying positive effect of barley.

In theory, there may be temporal complementarity between winter crops and walnut trees. Namely, walnut is a late leafing deciduous species, so shading by its canopy that occurs during later barley development may not have a critical limiting effect on barley yield. Furthermore, barley is a C3 plant, which means it is less susceptible to negative effects of shading, as only 50% of full sunlight is enough for the plant to become fully light-saturated [4]. Similarly, belowground, walnut fine root production peaks during the summer months [31,32], and by this time, most winter crops, including barley, are already fully developed and have captured most of the nutrients and water from the soil [5]. In favor of this temporal complementarity hypothesis are findings by Liu et al. [33]. The authors showed that walnut consumes most of the water in the fruit expansion stage during the summer months, and the sources of that water are mostly deeper soil layers.

Although the soil water content at sowing and harvest showed that intercropped systems of walnut and barley had more water than monoculture barley, it is unknown how it was distributed through vegetation and how it was shared between barley and walnut. Still, barley yield and water productivity in intercropped systems in both locations were lower than in their monoculture systems. In addition, barley pLERC and pWERC were lower in Ivankovo than in Đakovo. Shading by larger tree canopies in Đakovo probably affected barley productivity. However, in Ivankovo, where walnut trees are spaced widely and smaller canopies do not overcast significant shading on the understory, a belowground competition was probably the main driver of the walnut–barley system's productivity, and it may be correlated to a rooting pattern. Generally, tree water consumption increases with tree age, so the root system tends to grow deeper to meet increasing water requirements [34]. Accordingly, younger trees prefer to extract water from shallower soil layers in the cropping zone, where most of their roots are [35]. Consequently, stronger competition for water and nutrients can occur in intercropped systems and thereby cause a more significant reduction in crop yields. Zhao et al. [30] observed that most of the lateral roots of 4-year-old jujube trees were spread in up to 30 cm of soil depth, while older jujube trees had a majority of their lateral roots around 60 cm of soil depth. This may have caused a greater reduction in understory peanut yield under younger jujube trees. Furthermore, the soil in Ivankovo has a higher bulk density, and it is generally more compact than the soil in Đakovo, especially in the subsoil layer. Such soil can limit trees' vertical root growth and cause more pronounced lateral spreading of walnut roots, which then interfere with crops roots. On the other hand, considering this hypothesis and high buckwheat yield in the intercropped orchard in Ivankovo, it seems that buckwheat roots, despite low total mass, have a good absorption power [36] and have ensured high productivity, even in competition with young walnut trees.

The water balance equation showed that the walnut–barley intercropped system in Ivankovo used more water than the monoculture barley and much more than the Đakovo systems. In fact, the WU values were consistently greater in Ivankovo than in Đakovo, and these differences can partially be explained by differences in the amount of rainfall and other climatic conditions, which may have been different between the two locations. Furthermore, our observations showed that a decrease in water use (i.e., ETC) in intercropped systems compared to crop monoculture and sole orchard systems was more pronounced in Đakovo. Liu et al. [16] found that the dense crown of Populus in intercropped system decreased radiation and wind speed, which led to a higher contribution of plant transpiration to total ET rather than soil evaporation. Even though the differentiation between plant transpiration and soil evaporation was not assessed in this study, considering our observations as well as previous studies, it seems that shading by large canopies of walnut trees did contribute to the reduction in soil evaporation [37]. Another possible effect that may help intercropped systems retain more water in the topsoil is hydraulic lift by deeper tree roots [30]. Additionally, a higher ET was observed during buckwheat vegetation, which can be ascribed to warmer summer conditions and higher tree transpiration rates due to increased walnut growth during these months.

5. Conclusions

Intercropping with trees, through various mechanisms, can ensure maximum utilization of available soil water, which, in theory, can increase yields without the need for additional irrigation. However, previous research, including ours, confirms that intercropping with trees is not a universal solution for achieving high yields and improved water utilization and that species selection and system design can be crucial factors. Considering the positive effect of trees on microclimatic conditions, our observations suggest that the primary limiting factor in older and denser orchards may be light, especially for summer crops sensitive to reduced radiation transmittance. On the other hand, in younger orchards with smaller canopies but shallower tree roots, water competition has a more significant effect on intercrop performance than the lack of light. Although these competitive interactions can be reduced by proper tree management, such as branch pruning or even root pruning, those can be labor-intensive and expensive and should be repeated frequently. Therefore, it is necessary to ensure proper tree spacing when establishing intercropped systems, but good practice could also be to sow competitive crops in the first years of intercropping. Highly competitive crop roots could suppress tree roots' lateral spreading and enhance their vertical growth, ensuring belowground spatial complementarity between future intercrops and trees. In older, mature orchards, reduction in competition can be based on ensuring temporal complementarity by choosing winter crops, such as barley.

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