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Crop Growth and Yield in Three-Crop Mixtures and Sole Stands in an Organic System

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Abstract

Low yields remain a primary obstacle to the expansion of organic farming in Europe. While legume-based mixed cropping enhances land-use efficiency, three-crop mixtures remain understudied compared to binary systems. We evaluated the vegetative and generative growth of pea (*Lathyrus oleraceus* Lam.), oats (*Avena sativa* L.), and camelina (*Camelina sativa* (L.) Crantz.) in sole stands versus three-crop mixtures in southern Finland. Experiments were conducted over two years using varying relative seeding densities (including 50:20:30, 50:50:50, and 33:33:33). Biomass dynamics and seed quality were analyzed using analysis of variance (ANOVA), while interspecific interactions were quantified using the relative interaction index (RII) and land equivalent ratio (LER). In 2022, mixtures increased oat seed protein by 11% relative to sole crops, achieving a biomass LER of 1.17. In 2023, oats exhibited strong competitive dominance (RII > 0.3), which concurrently reduced camelina quality. Notably, the 33:33:33 mixture consistently achieved a biomass LER > 1.2 and marked improvements in pea growth rates. Across all mixtures, the seed yield LER reached 1.04. These results suggest that three-crop mixtures can enhance productivity in Nordic organic agriculture with minimal quality trade-offs. Practically, we recommend the equal seeding density (33:33:33) as the optimal configuration for maximizing resource use efficiency, though further optimization of species combinations is encouraged.

Keywords: competition; generative growth; growth rate; land equivalent ratio; seed quality; biomass accumulation; crop interaction

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1. Introduction

While conventional agricultural systems have substantially enhanced crop yields and food security, their environmental costs pose critical sustainability challenges. Contemporary research documents significant detrimental impacts to terrestrial ecosystems, including biodiversity loss, soil degradation, and unsustainable water consumption patterns [1]. These externalities have prompted international policy initiatives promoting ecological intensification, with organic farming systems emerging as a key transitional strategy [2]. The European Union (EU) exemplifies this paradigm shift through its ambitious

Farm to Fork and Biodiversity Strategies under the European Green Deal framework [3]. These coordinated policies establish quantifiable targets for sustainable agriculture, most notably requiring 25% of EU agricultural land to achieve organic certification by 2030. This target represents a 150% increase from current levels, as Eurostat data reveal that only 9.6% of utilized agricultural area met organic standards in 2021 [4].

While organic agriculture demonstrates clear ecological benefits over conventional systems, its widespread adoption faces persistent economic barriers. Yield gaps of 19–25% compared with conventional systems are largely attributable to restricted chemical inputs [5]. Legume-based intercropping has been proposed as one approach to narrow down the existing yield gap. Incorporating legumes into intercropping systems improves the efficiency of light, water, and nutrient use, enhances weed control, and reduces pest and disease incidence [6,7]. Furthermore, complementary interspecies resource partitioning, such as polycultures, can enhance yield stability while reducing synthetic fertilizer dependence by 30–40% [8]. The increased activity of rhizobacteria in leguminous crops is directly linked to the enhanced availability of nitrogen (N) and phosphorus in the soil, which significantly contributes to the high-yield advantages of mixed crops [9]. The interaction not only boosts rhizosphere microbial activity but also facilitates the activation of insoluble nutrients, promotes resource sharing, stabilizes soil organic matter, and enhances N transfer between legumes and adjacent crops. The symbiotic efficiency can reach as much as 30–65 N kg ha^{-1} in cereal–legume systems [10]. Diversified intercropping systems deliver synergistic benefits across multiple agricultural dimensions: land equivalent ratios (LER) consistently exceed 1.2–1.4 in optimized combinations; N mineralization rates increase by 15–25% with simultaneous 20% improvements in phosphorus bioavailability; and carbon sequestration potentials reach 0.5–1.2 Mg C ha^{-1} yr^{-1} through enhanced root exudation and microbial activity [11–13].

Pea (*Lathyrus oleraceus* Lam.) plays a pivotal role in advancing sustainable agriculture, primarily by enhancing soil N availability through biological nitrogen fixation. This process relies on the symbiotic association with Rhizobium bacteria within root nodules, which convert atmospheric nitrogen into ammonia. Furthermore, the release of N-rich root exudates and the decomposition of legume residues facilitate N transfer to neighboring non-legume crops, a mechanism often enhanced by the rhizosphere priming effect. Pea–oats (*Avena sativa* L.) intercropping outperforms monoculture in terms of both economic and land-use efficiency [14], and has been found to increase the protein content of the cereal grain [15]. Oats, with their deeper and more rapidly growing root system, are more efficient at absorbing mineral N, which helps to create N niches between pea and oats, thus reducing mixed-crop competition [16]. In organic farming systems, pea–oats intercropping is relatively common, as it enhances weed control and supports the establishment of pea populations. However, positive effects have not always been recorded for weed suppression, total biomass, or grain yield [15,17]. The increasing interest in intercropping systems has also spurred the revival of underutilized crops, such as camelina (*Camelina sativa* L. Crantz). Camelina is gaining attention for its low energy input requirements, strong environmental adaptability, and excellent resistance to pests and diseases [18,19]. Van Staden et al.'s research reported the weed suppression effect in the pea–false flax intercropping system [20]. Elena Pagani found that when camelina is intercropped with lentils, both the 1000-seed weight and the α-linolenic acid content increase significantly [21]. All these indicate that the intercropping of camelina and legumes has broad prospects. Consequently, these three species were selected to construct a functionally diverse community comprising a legume (pea), a cereal (oats), and an oilseed (camelina). This specific combination allows for the evaluation of niche complementarity—integrating biological nitrogen fixation, varying rooting depths, and distinct canopy architectures—as a mechanism to enhance resource use efficiency. By combining these functional groups, the study aims to determine if increasing biological complexity can overcome the productivity constraints typical of high-latitude organic farming.

Research on the vegetative and generative relationship in crop production is crucial [22]. An in-depth understanding of this relationship is essential for improving crop growth and yield in intercropping systems. The theory suggests that leaves, as the primary organs for photosynthesis, contribute approximately 95% of the dry matter through photosynthetic products, with the remaining 5% derived from mineral nutrients. Therefore, key factors influencing the supply of assimilates include the effective leaf area index and the photosynthetic rate. However, yield is not only determined by the accumulation rate of photosynthetic products but also by the efficiency with which the generative part absorbs carbohydrates [23]. In intercropping systems, however, the impact of competition and mutual promotion between crops regarding this relationship remains uncertain. Given this context, the objectives of our study were to investigate the growth of three-crop mixtures and sole-crop stands of pea, oats, and camelina, and to quantify the dynamic changes in the vegetative and generative relationship during crop growth under mixed cropping in an organic farming system.

2. Materials and Methods

2.1. Study Site and Experimental Design

Two field experiments were conducted in 2022 and 2023 at an organic farm in Hyvinkää, southern Finland (N 60°59′ E 24°92′, 84 m above sea level). In 2022, the soil was silt loam with 15% clay, 55% silt, and 30% very fine or fine sand, and a pH_{water} of 5.9. In 2023, the soil was loam with 28% clay, 48% silt, and 24% very fine or fine sand, and a pH_{water} of 6.3. The soil organic carbon (SOC) content of the topsoil (0–20 cm) was 24.3 g kg^{-1} in 2022 and 31.5 g kg^{-1} in 2023. Total soil N content of the topsoil was 1.5 g kg^{-1} in 2022 and 2.3 g kg^{-1} in 2023. The soils were tentatively classified as Endogleyic Regosol in 2022 and Endogleyic Eutric Cambisol in 2023 (IUSS Working Group WRB 2015).

In the 2022 field experiment, the pre-crop was a 4-year forage grass mixture harvested once during summer 2021. In the 2023 field experiment, the pre-crop was winter rye (*Secale cereale* L., 'Walet') with white clover (*Trifolium repens* L., 'Huja') as a companion crop sown in 2021 and harvested in 2022. The experimental area was non-inversion tilled with a cultivator to a depth of 20 cm during the preceding autumn. In the spring, one week before seeding, the area was disc harrowed twice to a depth of 10 cm and once immediately before seeding.

The experiment included the three-crop mixtures and pure stands of oats ('Ivory'), pea ('Astronaute'), and camelina (landrace). Sole stand seeding densities were 600 viable seeds m^{-2} camelina, 500 viable seeds m^{-2} oats, and 120 viable seeds m^{-2} pea. The mixtures were sown at various seeding densities. The relative species seeding densities (%) in pea/oats/camelina mixtures were 50:20:30 and 33:33:33 in 2022 and 50:50:50 and 33:33:33 in 2023, based on their respective pure stand seeding densities. The experiments were arranged in a randomized complete block design with four replicates. Plot size was 1.5 m × 15 m.

Pea, oats, and camelina were sown on 19 May in 2022 and 2023 with a plot seeder (Wintersteiger TC2700, Wintersteiger AG, Ried, Austria). To ensure optimal establishment for each species, sowing was performed in two consecutive passes in the mixed plots. First, pea and oats were sown at a depth of 5 cm, followed by camelina at a depth of 1 cm in the same plots. Row spacing was 12.5 cm. No fertilizer or pesticides were used.

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2.2. Sampling and Measurements

The emergence rate of each crop species was recorded from 3 × 50 cm rows within each plot at the two-leaf stage [24]. Growth stages were monitored weekly after emergence. Pests and diseases were monitored three times during the growing season and before the harvest. To ensure representativeness, samples were collected by uprooting all plants from a randomly selected 0.25 m^{-2} (50 × 50 cm) area within the central rows of each plot, avoiding the edges to minimize border effects. Samples were collected at the tillering, stem elongation, anthesis, grain filling, and yellow maturity stages during both years. Plants were shaken gently to remove loose soil from the roots. The crop species were separated and counted. Main stems and tillers were separated and further divided into vegetative and generative parts. Vegetative parts were further divided into leaves and shoots. The number of tillers, main stems, generative parts, and seeds was counted. Samples were dried in an oven at 105 °C for 1 h, followed by continued drying at 65 °C to constant weight. Dried samples were ground into fine powder (1 mm sieve, ZM 200, Retsch GmbH, Haan, Germany). An intact 10 m^2 area was harvested with a plot combine (Wintersteiger Classic Plus, Wintersteiger AG, Austria) at full maturity on 26 August 2022 and 6 September 2023. The seeds were dried and fractionated by species (seed sorter, Westrup A/S, Slagelse, Denmark) and weighed. Following separation, quality measurements were conducted using identical protocols for both sole crops and the sorted components of the mixtures to ensure consistency. Seed moisture content was determined by drying 1 g of seeds at 105 °C for 24 h.

1000-seed weight was measured from the dried and sorted seeds by counting out 100 seeds four times and weighing them. Protein content was determined from dried and ground seeds with the Dumas combustion method (CN 828, Leco Corp., St. Joseph, MN, USA) and by multiplying the result by 6.25. Test weight was measured from dried and sorted oats seeds. Crude fat content of camelina seeds was analyzed from a 10 g subsample of dried and sorted seeds that were ground into fine powder (1 mm sieve, Retsch ZM200). Samples were hydrolyzed with 800 mL of HCl (4 mol L^{-1}) (SoxCap 2047 hydrolysis unit, FOSS Analytical, Hillerød, Denmark) following extraction with 90 mL of petroleum ether (FOSS Soxtec 8000 extraction unit, FOSS Analytical, Hillerød, Denmark).

2.3. Calculations and Indices

The sigmoid growth function was calculated according to Yin et al. [25] as follows:

$$W = \begin{cases} W_{max}\left(1 + \frac{t_e - t}{t_e - t_m}\right)\left(\frac{t}{t_e}\right)^{\frac{t_e}{t_e - t_m}} & 0 \leq t \leq t_e \\ W_{max} & t > t_e \end{cases} \quad (1)$$

where W represents the dry matter (vegetative or generative) at time t; W_{max} is the total dry matter accumulation, t is the number of days after emergence, t_e is the time of maximum dry matter accumulation, t_m is the time when the growth rate is at its maximum. Further, based on Equation (1), the growth rate can be expressed as:

$$R_r = \frac{dW}{dt} = R_m\left(\frac{t_e - t}{t_e - t_m}\right)\left(\frac{t}{t_m}\right)^{\frac{t_m}{t_e - t_m}} \quad (2)$$

$$R_a = \frac{W_{max}}{t_e} \quad (3)$$

$$R_m = W_{max}\left(\frac{2t_e - t_m}{t_e \times (t_e - t_m)}\right)\left(\frac{t_m}{t_e}\right)^{\frac{t_m}{t_e - t_m}} \quad (4)$$

where R_r is growth rate (vegetative or generative); R_a is average maximum growth rate; R_m is maximum dry matter growth rate.

The relative interaction index (RII) was used to assess the interspecific competition among crops in mixed treatments, as defined by Armas et al. [26]:

$$RII = \frac{B_{mix,i} - B_{sin,i}}{B_{mix,i} + B_{sin,i}} \quad (5)$$

where $B_{mix,i}$ is the average biomass of species i in the mixed treatments, $B_{sin,I}$ is the average biomass of species i in the monoculture.

LER, which describes the land use efficiency of intercropping compared to monocropping, was calculated following Mead and Willey [27]:

$$LER = \frac{Y_1}{M_1} + \frac{Y_2}{M_2} \quad (6)$$

where Y_1 and Y_2 are the yields of species 1 and 2 in the mixed crops and M_1 and M_2 are the yields of species 1 and 2 in the sole crops, respectively.

2.4. Weather Conditions

During the growing seasons of 2022 and 2023, air temperatures were slightly higher than the long-term average (1991–2020), with July and August of 2022 being particularly warm (Table 1) (Finnish Meteorological Institute). In 2022, precipitation was generally below the long-term average throughout the growing season, except for a relatively rainy July. By contrast, 2023 experienced below-average rainfall in May and June, followed by higher-than-average precipitation in July, August, and September.

Table 1. Monthly mean temperatures and precipitation at the field experiment site during growing seasons 2022 and 2023, and the long-term means for 1991–2020 at Hyvinkäänkylä, Hyvinkää, Finland (FMI 2024).

	Temperature, °C			Precipitation, mm		
Month	**2022**	**2023**	**1991–2020**	**2022**	**2023**	**1991–2020**
May	13.1	13.2	10.2	39	16	40
June	17.7	17.0	14.5	33	46	65
July	18.2	16.8	17.3	55	92	70
August	18.6	16.7	15.5	44	225	75
September	8.6	14.3	10.5	37	72	54
October	7.6	7.8	4.8	9	62	67

2.5. Statistical Analysis

Statistical analyses were performed using SPSS software (Version 22.0 and 29.4, IBM, Inc., Armonk, NY, USA). Levene's test was used to assess the homogeneity of variances, with the significance level set at $p = 0.05$. A one-way analysis of variance (ANOVA) was conducted to assess the effects of the cropping system in a randomized complete block design. Differences among treatment means were evaluated using Duncan's multiple comparison test, with a significance level set at $p < 0.05$. Additionally, the effects of crop types on various indices were analyzed, and significant differences were identified using Duncan's test.

3. Results

3.1. Dry Matter Accumulation

In 2022, dry matter accumulation in the vegetative plant parts (leaves and stems) of oats in the sole stand was significantly lower than that of oats in mixtures (Figure 1). At 71 days after sowing (DAS), the vegetative mass of oat in the sole stand was 0.98 g plant^{-1} and in the mixtures 1.37–1.45 g plant^{-1}. By contrast, the vegetative mass of pea was highest in the sole stand. At 71 DAS, the vegetative mass of pea in the sole stand was 3.43 g plant^{-1} and 2.18–2.59 g plant^{-1} in mixed stands. The vegetative mass of camelina in mix 50:20:30 and in the sole stand was higher than in mix 33:33:33. At 71 DAS, the vegetative mass of camelina was approximately 0.41 g plant^{-1} in the sole stand and in mix 50:20:30 and only 0.24 g plant^{-1} in mix 33:33:33.

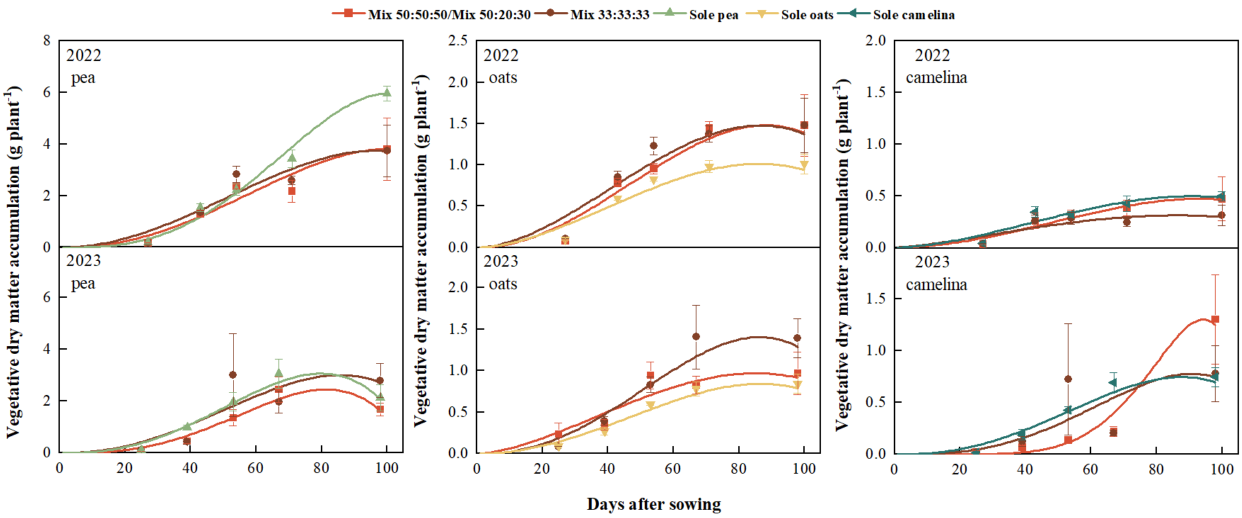

Figure 1. Accumulation of vegetative (leaf and stem) mass of pea, oats, and camelina in sole crops and their three-crop mixtures in a field experiment in Hyvinkää, Finland, in 2022 and 2023. Data shown are means ± SE, n = 4. Mix 50:50:50, mixture of 50% pea, 50% oats, 50% camelina; mix 50:20:30, mixture of 50% pea, 20% oats, 30% camelina; mix 33:33:33, 33% pea, 33% oats, 33% camelina.

In 2023, the vegetative mass accumulation of oats was highest in mixed stands (Figure 1). At 98 DAS, the vegetative mass of oats was 0.84 g plant^{-1} in the sole stand, 0.98 g plant^{-1} in mix 50:50:50, and 1.39 g plant^{-1} in mix 33:33:33. At 98 DAS, the vegetative mass of camelina was highest (1.30 g plant^{-1}) in mix 50:50:50, whereas it was 0.74 g plant^{-1} in the camelina sole stand. In 2022, the maximum generative mass (panicles, seeds) of oats in mixtures was slightly higher (1.35 g plant^{-1}) in mix 50:20:30 and in mix 33:33:33 (1.31 g plant^{-1}) compared with the generative mass of oats in the sole stand (0.78 g plant^{-1}) at 100 DAS (Figure 2). The generative mass of pea (flowers, pods, seeds) was 3.48–3.55 g plant^{-1} in mixed stands and 3.13 g plant^{-1} in the sole stand at 100 DAS. The generative mass (racemes, flowers, siliqua, seeds) of camelina was highest in the sole stand, 0.15 g plant^{-1}, at 100 DAS, followed by the vegetative mass of camelina in mix 33:33:33 (0.09 g plant^{-1}).

In 2023, at 98 DAS, the generative mass of oats was highest in mixed stands, being 1.20 g plant^{-1} and 1.56 g plant^{-1} in mix 50:50:50 and mix 33:33:33, respectively, compared with the generative mass of oats in the sole stand (10.01 g plant^{-1}) (Figure 2). At 98 DAS, the generative mass of pea was highest in mixed stands, being 1.20 g plant^{-1} in mix 50:50:50, 1.56 g plant^{-1} in mix 33:33:33, and 1.01 g plant^{-1} in the sole stand. In 2023, camelina accumulated generative biomass slowly in mix 50:50:50 during the initial growth period, but the accumulation rate increased sharply between 67 and 98 DAS. By 98 DAS, camelina in the sole crop had the lowest generative mass (0.69 g plant^{-1}).

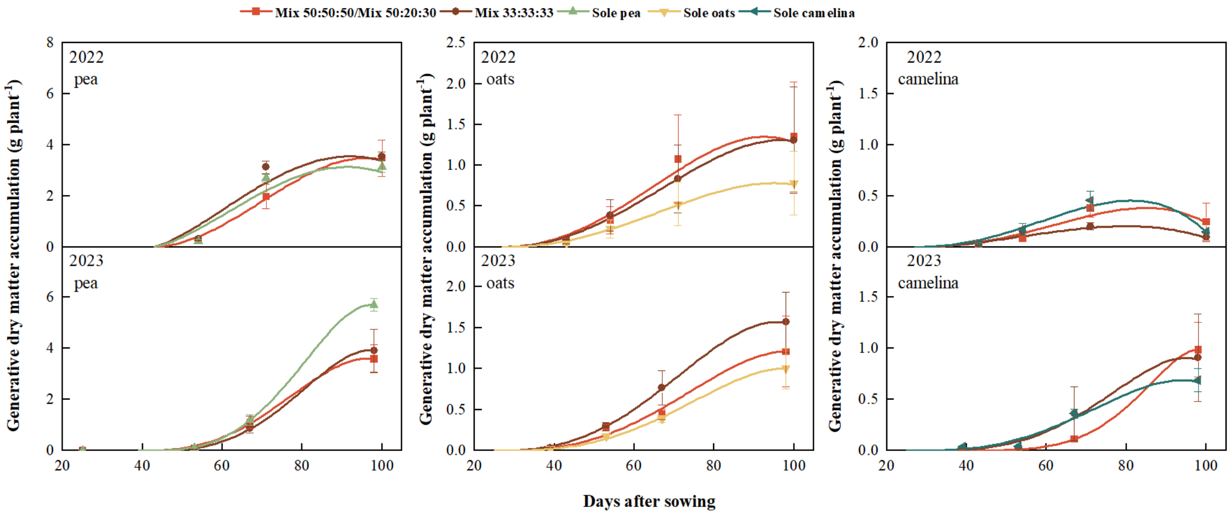

Figure 2. Accumulation of generative (seed and grain) mass of pea, oats, and camelina in sole crops and their three-crop mixtures in a field experiment in Hyvinkää, Finland, in 2022 and 2023. Data shown are means ± SE, *n* = 4. Mix 50:50:50, mixture of 50% pea, 50% oats, 50% camelina; mix 50:20:30, mixture of 50% pea, 20% oats, 30% camelina; mix 33:33:33, 33% pea, 33% oats, 33% camelina.

In 2022, the average and maximum growth rates of oats in the sole stand were higher compared with the growth rate of oats in mixed stands (Figure 3). In the growing seasons of both 2022 and 2023, pea in mixtures had the lowest rates of vegetative and generative dry matter accumulation. However, this differed between years, as mix 50:20:30 had the highest growth rate in 2022 and mix 33:33:33 in 2023. Camelina growth rate was highest in the sole stand in 2022, but its generative mass growth rate declined to nearly zero at 80 DAS. By contrast, camelina growth rate was highest in 2023 in mix 50:50:50. In 2023, oats had the highest growth rate in the sole stand. During the vegetative phase of oats, the average and maximum growth rates in the sole stand were over 21% higher compared with mix 50:50:50. The highest generative mass growth rate of oats was also in the pure stand, exceeding that of mix 50:50:50 by 60% and mix 33:33:33 by 46% (Table 2).

Table 2. Estimated parameter values of crop growth for vegetative and generative growth during growing season 2022 in the field experiment at Hyvinkää.

		Estimates for Vegetative Growth						Estimates for Generative Growth					
Crop Stand	**Species**	**Wmax**	**tm**	**te**	**ra**	**rm**	**R^2**	**Tmax**	**Tm**	**Te**	**Ra**	**Rm**	**R^2**
								2022					
Mixture 50:20:30	Pea	1.48	88.08	46.91	0.01	0.03	0.94	1.35	66.72	38.67	0.02	0.03	0.98
	Oats	3.81	99.93	58.03	0.04	0.06	0.89	3.49	53.85	27.87	0.06	0.1	0.99
	Camelina	0.47	93.03	48.07	0	0.01	0.93	0.38	58.94	35.83	0	0.01	0.92
Mixture 33:33:33	Pea	1.48	86.96	41.04	0.01	0.03	0.9	1.31	70.76	40.78	0.02	0.03	0.99
	Oats	3.75	95.92	51.09	0.04	0.06	0.88	3.56	49.11	17.93	0.06	0.1	0.93
	Camelina	0.31	86.01	29.05	0	0.01	0.7	0.2	53.98	28	0	0.01	0.9
Sole crop	Pea	1.01	86.09	39.98	0.01	0.02	0.91	0.78	69.11	40.38	0.01	0.02	0.99
	Oats	5.95	100.09	68.05	0.06	0.11	0.98	3.14	49.4	18.91	0.05	0.09	0.94
	Camelina	0.5	90.93	41.03	0	0.01	0.91	0.45	55.13	32.76	0	0.01	0.97

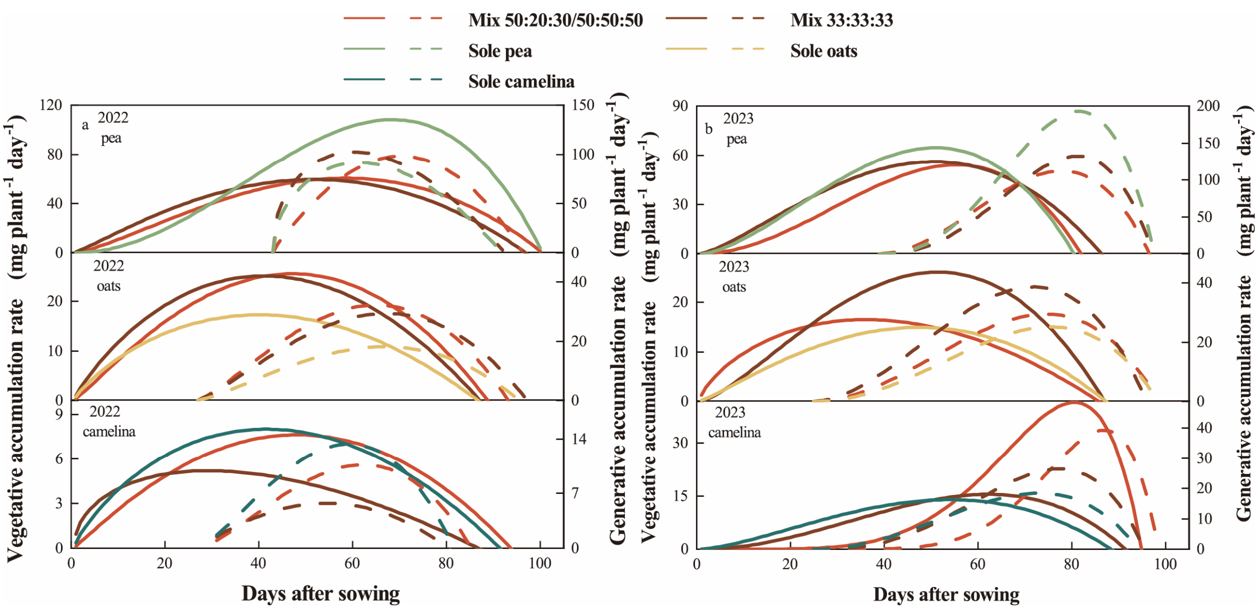

Figure 3. Simulated growth rate of vegetative parts (leaves and stem) and generative parts (seeds and grains) of pea, oats, and camelina pure stands and their three-crop mixtures in (**a**) year 2022 and (**b**) year 2023. Solid lines represent the vegetative accumulation rate, dashed lines represent the generative accumulation rate. Mix 50:50:50, mixture of 50% pea, 50% oats, 50% camelina; mix 50:20:30, mixture of 50% pea, 20% oats, 30% camelina; mix 33:33:33, 33% pea, 33% oats, 33% camelina.

In 2022, in mixed stands, especially mix 33:33:33, the maximum growth rate of pea increased up to 64% and up to 75% during the vegetative and generative phases, respectively (Figure 3). In 2023, the growth rate of camelina was affected by mixed cropping, as the average growth rate in mix 50:50:50 increased by over 33% and the maximum growth rate increased over 43% relative to camelina in the sole stand (Tables 2 and 3). Overall, the impact of mixed cropping on growth rates varied notably across species. Oats showed the highest growth rate in the sole stand, whereas pea and camelina had the highest growth rates in mix 33:33:33 and mix 50:50:50, respectively. Although the growth rate of oats in the sole stand was higher than in the mixed crop stand in 2023, the difference was less pronounced in 2022. Pea and camelina both had higher growth rates in mixed cropping in 2023.

Table 3. Estimated parameter values of crop growth for vegetative and generative growth during growing season 2023 in the field experiment at Hyvinkää.

		Estimates for Vegetative Growth						Estimates for Generative Growth					
Crop Stand	**Species**	**Wmax**	**tm**	**te**	**ra**	**rm**	**R^2**	**Tmax**	**Tm**	**Te**	**Ra**	**Rm**	**R^2**
							2023						
Mixture 50:20:30	Pea	0.97	85.09	36.04	0.01	0.02	0.83	1.21	73.65	50.06	0.02	0.03	0.98
	Oats	2.45	81.09	54.93	0.02	0.05	0.94	3.59	58.08	39.36	0.06	0.11	0.99
	Camelina	1.3	94	79.91	0.01	0.04	0.97	0.98	73.99	62.43	0.01	0.04	0.99
Mixture 33:33:33	Pea	1.4	85.93	50.91	0.01	0.03	0.94	1.57	71.54	47.41	0.02	0.04	0.99
	Oats	3.01	86.06	49.96	0.03	0.06	0.69	3.92	58.89	42.71	0.07	0.13	0.99
	Camelina	0.78	90.98	61.92	0.01	0.02	0.98	0.9	70.99	52.82	0.01	0.03	0.99
Sole crop	Pea	0.84	87.06	47.04	0.01	0.01	0.96	1	74.06	51.08	0.01	0.03	0.99
	Oats	3.07	80.08	50.06	0.02	0.06	0.96	5.7	47.13	25.69	0.09	0.19	0.99
	Camelina	0.74	88.09	53.96	0.01	0.01	0.96	0.69	69.76	48.55	0.01	0.02	0.98

The dry matter partitioning capacity and the vegetative-to-reproductive ratio (V-R) of oats differed significantly ($p < 0.05$) between the stand types (Table 4). Between years, significant effects were observed regarding the V-R difference and ratio of oats in the sole stand. In 2022, mixed cropping led to greater dry matter partitioning to the reproductive organs, with the oat V-R ratio in the sole stand being 80–83% higher than oats in mix 50:20:30 and mix 33:33:33. In 2023, mix 33:33:33 exhibited the highest V-R ratio.

Table 4. Vegetative (V) and generative (R) growth capacity (V-R) and ratio (V/R) of mixed crops and sole crops in a field experiment at Hyvinkää in 2022 and 2023. Different letters indicate significant differences.

	2022					
	Pea		**Oats**		**Camelina**	
Crop Stand	**V-R**	**V/R**	**V-R**	**V/R**	**V-R**	**V/R**
Mixture 50:20:30/50:50:50	0.32 b	1.06 b	0.13 a	1.24 a	0.22 a	3.55 a
Mixture 33:33:33	0.19 b	1.04 b	0.17 a	1.61 a	0.22 a	3.66 a
Sole crop	2.82 a	1.91 a	0.23 a	1.41 a	0.34 a	3.30 a
p-value	0.046	0.016	0.978	0.83	0.232	0.901
	2023					
	Pea		Oats		Camelina	
Crop stand	V-R	V/R	V-R	V/R	V-R	V/R
Mixture 50:20:30/50:50:50	−1.91 a	0.48 ab	−0.24 a	0.90 a	0.32 a	1.23 a
Mixture 33:33:33	−1.13 a	0.71 a	−0.18 a	1.07 a	−0.13 a	1.00 a
Sole crop	−3.56 b	0.38 b	−0.16 a	1.04 a	0.06 a	1.11 a
p-value	0.013	0.044	0.98	0.916	0.174	0.324

3.2. Seed Yield and Seed Quality

In 2022 and 2023, a significant difference was observed in the seed yield of oats, camelina, and pea between the different crop stands (Table 4). Seed yield was highest in sole oats, pea, and camelina. Seed yield decreased the most in mixed camelina stands compared with sole stands. We observed no differences in pea and camelina seed yields between mixed stands. However, oat seed yield was lowest in mix 50:20:30 in 2022 and in mix 33:33:33 in 2023 (Table 5).

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Table 5. Seed yield and yield quality traits of mixed crops and sole crops in field experiment at Hyvinkää in 2022 and 2023.

		2022			2023			*p*-Value		
Trait	**Species**	**Mixture 50:20:30**	**Mixture 33:33:33**	**Sole Crop**	**Mixture 50:50:50**	**Mixture 33:33:33**	**Sole Crop**	**Year (Y), df = x**	**Crop Stand (CS), df = x**	**Y x CS, df = x**
Seed yield, g m^{-2}	Pea	809 b	711 b	1824 a	540 b	704 b	3450 a	0.051	<0.001	0.004
	Oats	1320 c	2192 b	4078 a	3491 ab	2903 b	4143 a	<0.001	<0.001	0.004
	Camelina	107 b	109 b	606 a	44 b	812 b	749 a	0.771	<0.001	0.329
1000-seed weight, g	Pea	293.94 b	296.18 b	309.83 a	203.03 a	201.88 a	221.84 a	<0.001	0.044	0.909
	Oats	47.20 a	47.80 a	48.05 a	40.04 a	38.75 a	39.31 a	<0.001	0.873	0.496
	Camelina	1.20 a	1.22 a	1.15 a	1.11 a	1.07 ab	1.00 b	<0.001	0.026	0.5
TFC, g kg^{-1}	Camelina	392.4 a	403.5 a	422.3 a	343.3 b	325.1 b	398.2 a	<0.001	0.002	0.102
TW, kg hl^{-1}	Oats	49 a	50 a	50 a	48 a	47 a	48 a	0.017	0.992	0.614
Protein content, g kg^{-1}	Pea	0.25 a	0.25 a	0.25 a	0.31 a	0.30 ab	0.29 b	<0.001	0.005	0.074
	Oats	0.10 a	0.10 a	0.09 b	0.11 a	0.11 a	0.10 a	<0.001	0.007	0.671
	Camelina	0.21 a	0.22 a	0.20 a	0.21 b	0.21 b	0.23 a	0.028	0.064	<0.001

Note: TFC denotes total fat content; TW denotes test weight. Different letters indicate significant differences.

In general, all crops had higher 1000-seed weight in 2022 compared with 2023. In 2022, the 1000-seed weight of sole-crop pea was higher compared with pea in mixed stands (Table 5). By contrast, the 1000-seed weight of oats and camelina did not differ between the crop stands. Interestingly, in 2023, the 1000-seed weights of pea and oats were lowest in mix 33:33:33, while camelina seed weight was lowest in the sole-crop stand. In 2022, significant differences were observed only in oat protein content, which was highest in mix 33:33:33 and mix 50:20:30. In 2023, differences were observed in pea protein content, which was highest in mix 50:50:50, and camelina protein content, which was highest in the crop stand. In 2022, average camelina seed crude fat contents were equal in the different crop stands. However, in 2023, camelina seed crude fat content was highest in sole camelina compared with the mixed stands, while being lowest in mix 33:33:33. Moreover, camelina seed crude fat content was higher in 2022 than in 2023.

The test weight of oats was slightly higher in 2022 compared with 2023, averaging 49.7 kg hl^{-1} in 2022 and 47.7 kg hl^{-1} in 2023 (Table 5).

3.3. Land Equivalent Ratio and Relative Interaction Index of Crop Mixtures

We observed a significant difference in the LER of both seed yield and biomass yield between the crop stands studied in 2022 and 2023. In 2022, seed yield LER was highest in mix 33:33:33, being 1.12 in 2022 and 1.02 in 2023 (Figure 4). In 2022, mix 50:20:30 only reached 0.94, whereas mix 50:50:50 exceeded 1 in 2023, reaching 1.06. Dry matter LER was above 1 for both years in mix 50:20:30/50:50:50 and mix 33:33:33, with mix 33:33:33 showing the highest values, 1.17 in 2022 and 1.26 in 2023.

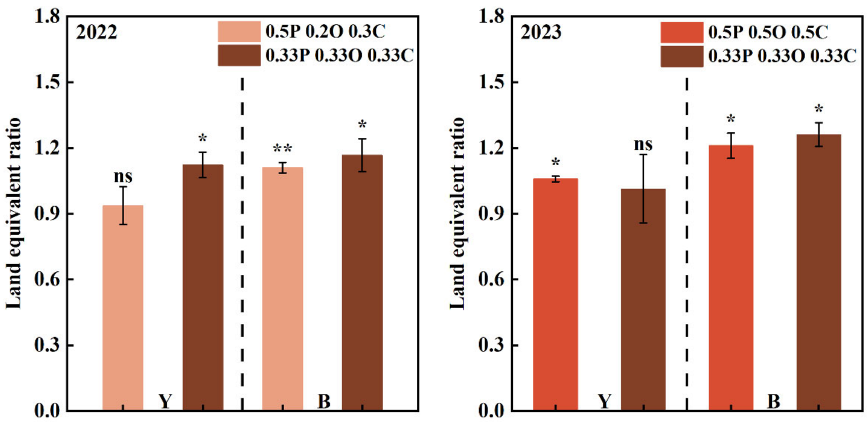

Figure 4. Land equivalent ratio (LER) of grain/seed yield and whole-plant biomass in the field experiment in Hyvinkää, Finland, in year 2022 and year 2023. Data shown are means ± SE, $n = 4$. Mix 50:50:50, mixture of 50% pea, 50% oats, 50% camelina; mix 50:20:30, mixture of 50% pea, 20% oats, 30% camelina; mix 33:33:33, 33% pea, 33% oats, 33% camelina; Y, yield; B, biomass; ns, not significant; *, $p < 0.05$; **, $p < 0.01$.

In 2022, RII was significantly affected by the studied crop stands (Figure 5). The RII of pea and oats was positive in mix 33:33:33. However, the RII of pea and oats in mix 50:20:30 was non-significantly positive. By contrast, the RII of camelina in mix 33:33:33 and mix 50:20:30 was non-significantly negative. In 2023, the RII of oats in mix 50:50:50 was significantly positive, whereas the RII of pea was non-significantly negative, and camelina was significantly negative (Figure 5). The RII of oats in mix 33:33:33 was significantly positive, and the RIIs of pea and camelina were non-significantly negative.

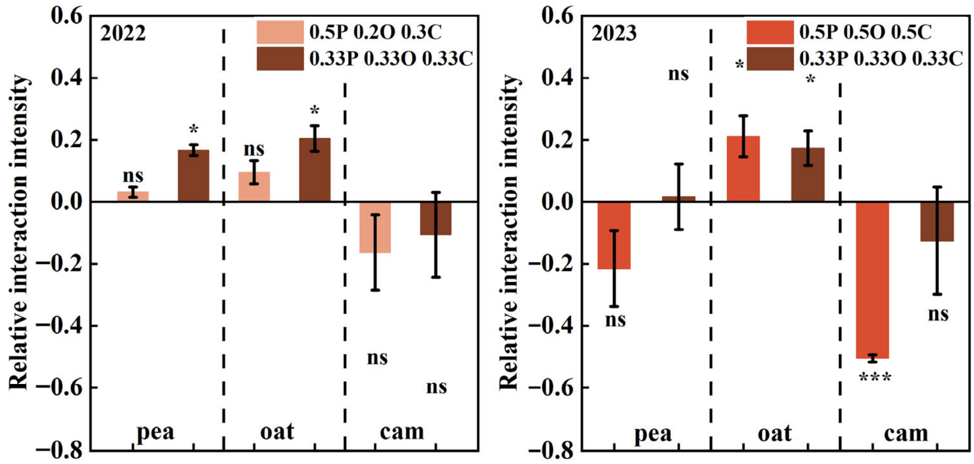

Figure 5. Relative interaction index (RII) of competition in sole stands and three-crop mixtures of pea, oats, and camelina in a field experiment in Hyvinkää, Finland, in 2022 and 2023. Data shown are means ± SE, n = 4. Mix 50:50:50, mixture of 50% pea, 50% oats, 50% camelina; mix 50:20:30, mixture of 50% pea, 20% oats, 30% camelina; mix 33:33:33, 33% pea, 33% oats, 33% camelina. ns, not significant; *, $p < 0.05$; ***, $p < 0.001$.

4. Discussion

In 2022, the vegetative dry matter accumulation of oats was significantly enhanced in mix 33:33:33 between 60 and 80 DAS compared with sole crops. However, at certain stages (e.g., 80–100 DAS), the vegetative dry matter accumulation in sole pea had decreased due to competition in the mixed crop. By contrast, in 2023, the generative dry matter of sole pea was significantly higher compared with that in the mixed crop. This suggests that, in the second year, pea had better capacity for dry matter accumulation during the reproductive stage, likely due to more favorable weather conditions that promoted later assimilate partitioning towards seed filling [14,28]. Generally, temperature and the distribution of precipitation are the key external environmental factors driving crop growth [29,30].

Different mixing ratios affected the crop growth rate, the timing of peak growth, and total growth duration. For example, in 2023, high-density mixed cropping (e.g., mix 50:50:50) reduced the growth rate of camelina but simultaneously increased the growth rate of oats. This outcome may be explained by the capacity of oats to rapidly gain a competitive advantage for light or space resources when grown with camelina and pea [15]. The growth rate of pea was also suppressed under mixed cropping in certain instances, particularly during the generative stage in 2023. In 2023, the seed number and single plant dry matter accumulation of pea in mixed stands were lower than in the sole crop, suggesting that the continuous decline in pea dry matter may be attributed to allelochemicals, such as phenolic acids, flavonoids, and terpenoids released by oats, which can inhibit plant elongation and photosynthetic activity [31]. This aligns with findings in binary systems where oat allelopathy contributes to weed suppression but can also affect companion crops [32]. Our results suggest that in ternary mixtures, particularly in years with vigorous oat growth (2023), this allelopathic potential—combined with asymmetric light competition—can create a cumulative stress that compromises the yield of subordinate species like pea and camelina, overriding the benefits of functional diversity. Beyond the climatic contrasts, resource competition almost certainly intensified the crop stand effects. Oat is an inherently leafy cereal that tillers profusely, expanding the canopy leaf area index early in the season. This dense upper canopy intercepts a larger share of incoming photosynthetically active radiation, lowers CO_2 concentration and relative humidity in the understory, and extracts soil moisture more rapidly than its companions. Such asymmetric capture of light, CO_2, and water can suppress the growth and seed filling of neighboring species and has been identified as a key driver of performance differences in cereal–legume mixtures. The high tillering capacity of cereals (including oat) enabled earlier and more efficient exploitation of the resources, thereby increasing the competitive pressure on the legume component [33].

Model analyses indicated that mix 50:20:30 slightly extended the time to reach peak growth compared with mix 33:33:33, thereby highlighting the stronger performance of camelina under mixed cropping. However, larger seeding proportions (e.g., mix 50:50:50) did not guarantee an extended growth period for all crops. For instance, in 2023, oats and pea under mix 50:50:50 exhibited shortened total growth duration and reduced time to reach peak growth, although camelina was unaffected. In high-density populations, the canopies of oats and pea closed rapidly. This leads to a steepening of the vertical gradient of light intensity. According to the plant light adaptation theory, when light intensity drops below the compensation point, crops will trigger a shade avoidance response [34]. This is manifested as elongated internodes and early flowering, thereby shortening the vegetative growth period [35].

LER based on biomass for most mixed crops exceeded 1, indicating that mixed cropping generally achieved higher overall resource use efficiency compared with sole crops in both the 2022 and 2023 growing periods. We nevertheless observed exceptions, such as mix 50:20:30 in 2022 and mix 33:33:33 in 2023, where yield LER values were not significantly above 1. While some mixed cropping combinations benefit from complementary interactions among the three crops (e.g., soil nutrient uptake via deep versus shallow roots), more intense competition in certain scenarios can reduce the net advantage. Fluctuations in precipitation and temperature, along with differences in seeding density, can sometimes diminish the benefits of specific mixed cropping combinations under particular environmental conditions [36].

Improved light and CO_2 availability, along with interspecies facilitation in mixed cropping systems, likely contribute to the increased oat yields. Conversely, the reduced pea yield can be attributed to the strong competitiveness of oats. We hypothesize that the taller stature and rapid canopy closure of oats created a shading effect that disproportionately limited the photosynthetic capacity of the lower canopy species. As noted in our results, oats exhibited superior vegetative growth rates, allowing them to intercept the majority of photosynthetically active radiation [20]. Pea, being less competitive compared with the taller oats, may experience inhibited stem elongation and leaf development. This, in turn, diminishes their photosynthetic capacity and the translocation of assimilates, ultimately leading to a decrease in yield [37]. The implications of this asymmetric competition are significant for organic system management. Since biological nitrogen fixation is an energy-intensive process, the reduced photosynthetic capacity of shaded peas limits the carbohydrate supply to root nodules, potentially compromising the N-fixation benefit of the mixture [38]. This suggests that while oats drive total biomass accumulation, their aggressive competitiveness can destabilize the functional balance of the system. Therefore, maintaining the pea population is not just about grain yield, but is essential for soil fertility. Future strategies imply a need to mitigate oat dominance, potentially by selecting cultivars with moderate tillering capacity or reducing oat seeding density further to safeguard the legume's ecological service.

The different crops benefited from mixed cropping in different years; oats exploited the mixed cropping environment more effectively in 2022, while pea experienced greater competitive pressure in 2023. Competition coefficient analyses confirmed these observations; in 2022, both pea and oats displayed positive competitiveness under mix 33:33:33, whereas oats generally emerged as the dominant species in mixed stands in 2023. Under mix 50:50:50, camelina was consistently at a competitive disadvantage. Several factors may account for these discrepancies. First, oats, being taller, typically capture light resources more effectively, particularly during early growth, whereas pea—which often exhibits prostrate or climbing growth—requires a more open environment and can easily be overshadowed by taller companions. Second, annual differences in weather, nutrient availability, and soil moisture significantly affect plant competition. If water deficit or nutrient deficiency occurs during critical growth stages (i.e., from vegetative growth through jointing or flowering), pea may be unable to fully leverage its symbiotic N fixation advantage [39]. In future research, attention should be paid to identifying mixed-crop species cultivars with similar phenology, complementary canopy architecture, rooting patterns, and nutrient-uptake strategies.

We observed no significant differences in 1000-seed weight between mixed and sole crops, which is similar to earlier observations by Bailey [40]. However, the 1000-seed weight in 2023 was notably lower than in 2022. This decline may be attributable to more intense competition or unfavorable weather conditions in 2023 that restricted the later growth and seed filling period, thereby reducing both seed filling rate and final seed weight [41].

Camelina seed oil content in the mixed crop was lower compared with the sole crop, suggesting that competition with oats and pea can limit the nutrient resources available for lipid synthesis [42]. Nevertheless, no significant difference was found in the hectoliter weight between mixed and sole crops, indicating that overall seed plumpness and uniformity were not notably affected by the mixed crop. Mixed cropping significantly increased the ratio of vegetative to generative growth stages in oats, enabling the plant to translocate more assimilates into its generative phase. From a physiological standpoint, the competitive pressure in mixed cropping appears to stimulate oats to maintain or even enhance the translocation of nutrients during the critical period of seed filling and reproductive organ development, ultimately boosting seed yield relative to vegetative tissue [43]. This phenomenon is particularly noteworthy for sustainable agriculture, as it demonstrates how certain species in a mixed cropping environment may develop compensatory mechanisms for reproductive output, ensuring a relatively stable yield despite interspecies competition.

Mix 33:33:33 yielded positive effects on pea, indicating that pea retains significant potential in mixed cropping systems. This benefit may be linked to the N-fixing ability of legumes, which can supply additional N both for their own needs and for neighboring crops, thus improving overall N utilization efficiency [44]. However, this ratio may not always be optimal under various climatic and soil conditions. Regardless of the mixing ratio, intercropping increased oat protein content in 2022 but reduced both the protein and fat content of camelina in 2023. A likely explanation is that the warm, moderately wet weather in 2022 boosted pea N-fixation and oat was able to take up the available N, resulting in increased seed protein content. In 2023, stronger competition for resources could have resulted in low seed protein and oil content in camelina.

Significant differences between 2022 and 2023 emphasize the strong weather dependence of mixed-crop performances. To optimize these mixtures for practical application, our results suggest that the balanced seeding ratio (33:33:33) offers a more stable trade-off between yield and quality than higher-density combinations. For future optimization, we recommend lowering the specific seeding density of the cereal component (oats) to mitigate its competitive dominance. Species combinations should be refined by selecting cultivars with complementary architectural traits—specifically, oat cultivars with moderate tillering capacity and pea cultivars with strong climbing ability. Beyond these agronomic adjustments, further investigation into crop interaction mechanisms—such as alterations in rhizosphere microbial communities and improvements in legume N-fixation efficiency—will provide the comprehensive scientific basis needed for sustainably managing these mixed cropping systems.

5. Conclusions

Yield performance, grain quality, and LER in organic mixed crops are sensitive to weather and species seeding ratios, and thus, competition. Across both seasons, mix 33:33:33 consistently maintained biomass LER > 1.2 and markedly improved pea growth and overall resource use, whereas mix 50:50:50 favored oat biomass accumulation but further suppressed camelina. The mixed crops treatment better helps local agriculture resist yield fluctuations under climate change. Three-crop mixtures of pea, oats, and camelina could be useful as an approach towards more stable yields and enhanced land-use efficiency of organic systems in the boreal–nemoral region. However, further studies are needed to determine the best-yielding seeding densities of the mixtures and to select the best cultivar combinations for pea, oats, and camelina to minimize yield-reducing competition.

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