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Crop Growth Analysis of Autumn- and Spring-Sown Wheat–Pea Intercrops

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Abstract: Intercropping of arable crops might provide yield benefits over monocrops. To assess the effect of sowing date and sowing ratio on biomass formation and competition over time, a two-year field experiment with wheat and pea plants was performed in Eastern Austria with two sowing times (autumn vs. spring) and with the following substitutive wheat–pea sowing ratios (%:%): 100:0, 75:25, 50:50, 25:75, 12.5:87.5 and 0:100. For both crops, facultative cultivars were used. Compared to spring-sowing, autumn-sowing resulted in earlier development of plants, taller plants, faster soil coverage, a higher crop growth rate up to mid-May in the first year and early June in the second year, more above-ground dry matter production and in the second year also in a higher land equivalent ratio (LER) of intercrops. Sowing ratios affected absolute and relative growth rates of wheat and pea plants. Wheat, which was generally the stronger partner in the intercrops, out-competed pea plants in all intercrops in the first year due to a higher early crop growth rate and in the second year, when the monocrop biomass of wheat was lower than that of pea plants, even in the intercrops with lower wheat and higher pea share. All intercrops resulted in a yield advantage compared to the monocrops as indicated by the LER. At final harvest, this yield advantage was over both sowing times and all four intercropping ratios 14% in the first and 10% in the second year. The competitive abilities of individual crops in mixtures, as indicated by the partial LER, were not affected by the sowing time.

Keywords: *Triticum aestivum*; *Pisum sativum*; absolute growth rate; relative growth rate; land equivalent ratio

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Academic Editor: Christos A. Dordas

Received: 4 January 2025
Revised: 30 January 2025
Accepted: 13 February 2025
Published: 16 February 2025

Citation: Neugschwandtner, R.W.; Herz, P.; Böck, A.; Wagentristl, H.; Moitzi, G.; Klimek-Kopyra, A.; Bernas, J.; Lošák, T.; Ghorbani, M.; Amirahmadi, E.; et al. Crop Growth Analysis of Autumn- and Spring-Sown Wheat–Pea Intercrops. *Agronomy* **2025**, *15*, 477. https://doi.org/10.3390/agronomy15020477

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1. Introduction

Cropping systems based on crop mixtures provide potential advantages compared to monocultures, including higher productivity and economic profitability, better control of pests and diseases and enhanced ecological services [1]. Intercropping affects the yield and yield component formation of crops through interspecific competition [2]. Intercropping can result in a low environmental impact, as shown by life cycle assessment [3], but also in a lower energy efficiency [4], as shown for oat–pea intercrops. Intercrops are mostly used in organic farming, but they can also be included in conventional systems, as a low nitrogen (N) fertilizer rate does not impair N_2 fixation, as shown in oat–pea intercrops [5].

In the coming decades, climate change is expected to cause higher temperatures and a shift in precipitation patterns in Central Europe, with an increase in precipitation in winter and early spring but less rainfall in summer. Consequently, in dry regions of Central Europe, there will be a decrease in rainfed summer crops with high water demand like peas, due to the increasing risk of drought damage [6]. Further, compared to spring-sowing, autumn-sowing results in higher grain yields and higher N yields, as shown for facultative wheat [7] and facultative triticale [8] sown in Austria. Therefore, there is increasing interest in winter grain legumes in Central European farming systems. Experiments in Austria in recent years have shown that winter faba beans and winter peas can have higher grain yields, protein yields and N fixation compared to spring faba beans and spring peas due to an extension of the duration of development stages and thus a higher biomass production and an increase in yield components, combined with an early onset of flowering and early harvest before the start of summer drought [9–11]. However, no yield advantage can be achieved if winter kill is high [12].

Most cereal–legume intercrop studies in Europe focus on spring-sown intercrops [2,13–16], whereas limited information is available on autumn-sown cereal–legume intercrops in continental Europe. Several studies have been performed for autumn-sown cereal–legume intercrops in France, e.g., [17]. Comparisons of autumn- and spring-sowing are also available for cereal–legume intercrops in Germany, e.g., [18,19], and England [20], with promising results for autumn-sown intercrops. Urbatzka et al. [18] have reported that winter pea plants in intercrops are more competitive compared to spring pea plants due to advanced development in spring. But in these studies, genotypes adapted to either of these sowing times were used, while no comparison of the same genetic material under both contrasting sowing times has been performed for cereal–legume intercrops. To close this gap for cereal–legume intercrops, a two-year experiment was conducted in Austria with facultative genotypes of wheat and pea plants sown either in autumn or in spring and with different sowing ratios to assess (1) crop development (2), plant height, (3) soil coverage, (4) crop growth, (5) above-ground dry matter production and (6) land equivalent ratios of wheat–pea intercrops as affected by sowing time and sowing ratio.

2. Materials and Methods

2.1. Experimental Site and Weather Conditions

The experiment was carried out in Raasdorf (48°14′ N, 16°33′ E) in Eastern Austria on the experimental farm Groß-Enzersdorf of the University of Natural Resources and Life Sciences, Vienna, in the 2010/11 and 2012/13 growing seasons. The soil is classified as a chernozem of alluvial origin and is rich in calcareous sediments (pH_{CaCl2}: 7.6, silty loam, organic matter: 2.2–2.3%). The mean annual temperature is 10.6 °C, and the mean annual precipitation is 538 mm (1980–2009) [21]. Long-term average monthly temperature and precipitation (1983–2012) from October to July and the values during the two growing seasons are shown in Figure 1. The average monthly temperature from March to June 2011 and from April to July 2013 was higher than the long-term average, with higher values in 2011 than in 2013 (except for July 2011). In 2013, snow fell after the sowing of spring-

sown treatments covering the field until early April, thereby considerably delaying the development and growth of the crops. Average precipitation in 2010/11 was generally below long-term values; in 2012/13, spring was dry, whereas there was more precipitation in May and June.

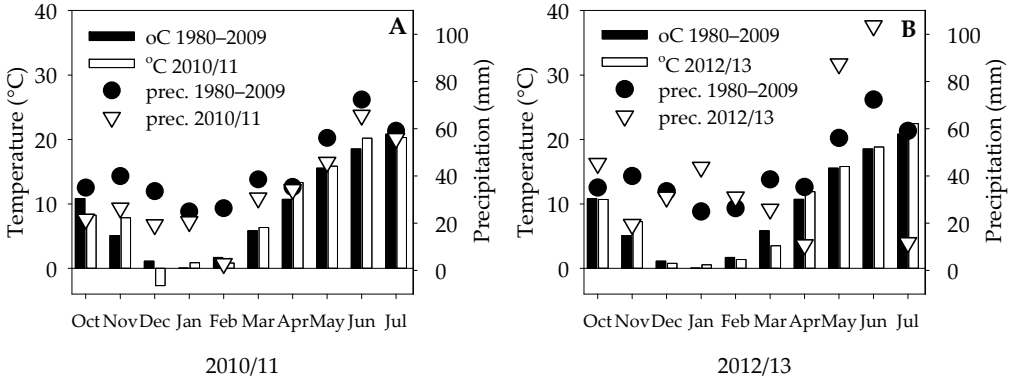


Figure 1. Long-term average monthly temperature and precipitation (1980–2009) and temperature and precipitation in the 2010/11 (**A**) and 2012/13 (**B**) growing seasons.

2.2. Experimental Treatments and Setup

Monocrops of wheat (*Triticum aestivum* L. cv. Xenos) and pea plants (*Pisum sativum* L. cv. Cherokee) were established with 300 (wheat) or 80 (pea) germinable seeds m^{-2}. Both are facultative cultivars that can be sown in autumn and in spring. The breeding company, country of origin and year of release are Strube Saatzucht GmbH & Co., KG, Germany and 1998 for Xenos and GAE Semences, France and 2007 for Cherokee. Monocrops represented a sowing rate of 100%. Four wheat–pea intercrops were sown in replacement series consisting of the following wheat–pea ratios (%:%, as compared to the monocrops): 75:25, 50:50, 25:75 and 12.5:87.5. Seeds were blended and sown in the same rows simultaneously. The sowing time was either autumn or spring. Dates are given in Table 1.

Table 1. Sowing and sampling dates in the two experimental years.

Year		2010/11		2012/13	
Sowing time		Autumn	Spring	Autumn	Spring
Sowing date		7 October 2010	14 March 2011	15 October 2012	12 March 2013
Sampling dates	1	15 March 2011	–	18 March 2013	–
	2	5 April 2011		11 April 2013	–
	3	27 April 2011		29 April 2013	
	4	17 May 2011		21 May 2013	
	5	8 June 2011		10 June 2013	
	6 [1]	4 July 2011	–	16 July 2013	–
	7 [2]	–	13 July 2011	–	25 July 2013

Final harvest of ([1]) autumn- or ([2]) spring-sown treatments.

Individual plots had an area of 15 m^2 (10 × 1.5 m) and comprised ten rows. Seedbed preparation was performed with a tine cultivator to a depth of 0.2 m. Soil mineral nitrate N (NO_3-N) at a depth of 0–0.9 m at sowing was 12.6 (7 October 2010), 16.8 (14 March 2011), 11.7 (15 October 2012) and 5.0 (12 March 2013) g N m^{-2}, respectively. The plots were not fertilized. Mechanical hand weeding was performed throughout the experiment. The plants were sprayed against pests when necessary with deltamethrin, 7.5 g a.i. ha^{-1} (Decis®). The experiment was established in a split-plot design: the sowing time was assigned to the main plots and the sowing ratio to the subplots. Four replications were performed.

2.3. Measurements

The BBCH scale [22] was used for phenological crop development description. The plant height of wheat and pea plants was measured manually throughout the experiment. The percentage of soil cover of the crops was measured during the growing period by color analysis of digital pictures according to Richardson et al. [23] and Karcher and Richardson [24] using SigmaScan Pro5 software. Digital photos were taken of every plot from a height of one meter above the ground. The development of above-ground dry matter was determined by harvesting (0.3 m^2 per plot) at intervals of about three weeks during the vegetative period and of 1.2 m^2 per plot at final harvest. Sampling dates (SDs) are summarized in Table 1. Plant samples were dried at 105 °C for 24 h.

2.4. Growth Analysis

Crop growth rate (CGR) and relative growth rate (RGR) were calculated for each period between subsequent sampling dates according to Hunt et al. [25] as follows:

$$\mathrm{CGR}\left(\mathrm{g\ m^{-2}\ d^{-1}}\right) = \frac{W_2 - W_1}{t_2 - t_1}$$

$$\mathrm{RGR}\left(\mathrm{mg\ g^{-1}\ d^{-1}}\right) = \frac{\ln W_2 - \ln W_1}{t_2 - t_1}$$

where W_2 and W_1 are the final and initial above-ground plant dry matter weight and t_2 and t_1 indicate the end and the start day of each period.

2.5. Land Equivalent Ratio

The land equivalent ratio (LER), which indicates yield advantages of intercrops over monocrops, was calculated according to Mead and Willey [26] as follows:

$$\mathrm{LER} = \frac{Y_{1.2}}{Y_{1.1}} + \frac{Y_{2.1}}{Y_{2.2}}$$

where $Y_{1.1}$ and $Y_{2.2}$ are the crop yields for crop 1 and crop 2 grown in monocrops, and $Y_{1.2}$ and $Y_{2.1}$ are the yields of the crops grown in intercrops. A LER > 1 indicates a yield advantage of the intercropping system, whereas a LER < 1 indicates a yield disadvantage. The LER is the sum of the partial LERs of the individual crops in intercrops. Partial LERs indicate the relative competitive abilities of individual crops in the intercrops.

2.6. Statistics

Statistical analyses were performed using SAS version 9.2. Analysis of variance (ANOVA) with subsequent multiple comparisons of means was performed. Means were separated by least significant differences (LSDs) when the F-test indicated factorial effects on the significance level of $p < 0.05$.

3. Results

3.1. Crop Development

Winter wheat (WW) entered winter rest in the two-leaf unfolded stage in 2010 and in the one-leaf unfolded stage in 2013. At sowing of spring wheat (SW) in mid-March 2011, WW had already reached the tillering stage, whereas this development stage was reached by WW in 2013 in the second week of April due to earlier cold temperatures and snow cover. SW started leaf development in early April in 2011 and in mid-April in 2013 due to the above-described climate conditions. By the end of April, WW was in stem elongation in both years, while SW was in tillering in 2011 and leaf development in 2013. In mid-May, WW was within booting and SW in the flag leaf stage in 2011 and in the flag leaf stage

(WW) and within stem elongation (SW) in 2013. In early June, WW was in early ripening and SW in fruit development in 2011 and in fruit development (WW) and at the end of flowering (SW) in 2013 (Figure 2A).

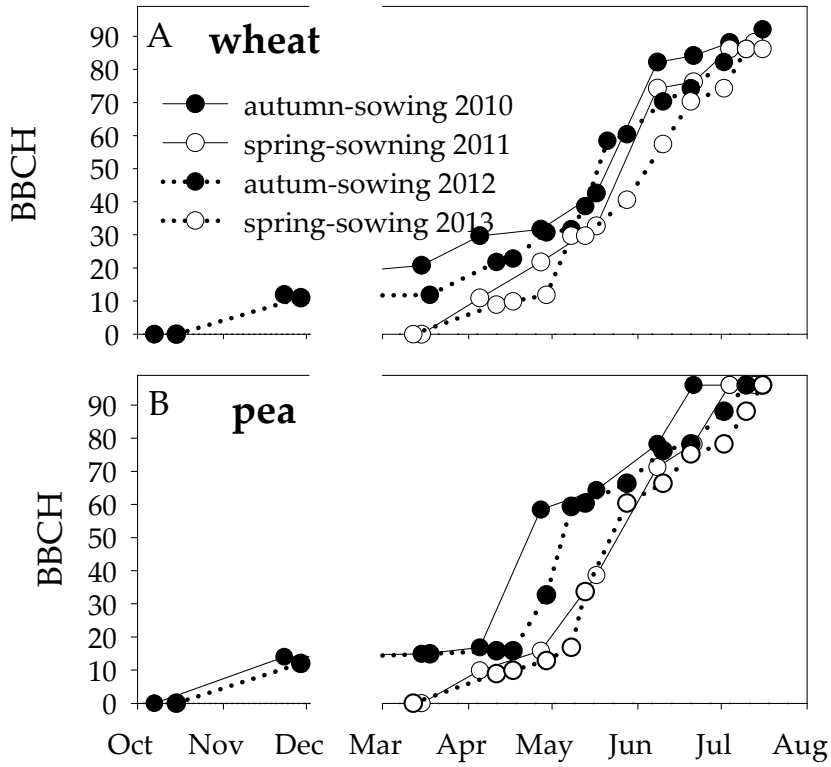


Figure 2. (**A**) Wheat and (**B**) pea crop development (BBCH stages) depending on sowing time in 2010/11 and 2012/13.

Winter pea plants (WP) entered winter rest in the four-leaf stage in 2010 and in the two-leaf stage in 2013. At sowing of spring pea plants (SP) in mid-March, WP had already reached the five-leaf stage in both years. SP started leaf development in early April in 2011 and in mid-April in 2013 due to earlier cold temperatures and snow cover. In mid-May, WP was within flowering and SP at the end of stem elongation in 2011 and in the start of flowering (WP) and within stem elongation (SP) in 2013. In early June, WP was ripening and SP in fruit development in 2011 and in early stage of fruit development (WP) and at the end of inflorescence emergence (SP) in 2013 (Figure 2B).

WW and WP were ripe for harvest in early July 2011 and SW and SP in mid-July in 2011 and in mid-July (WW, WP) and in the last part of July (SW, SP) in 2013.

3.2. Plant Height

Plant height is shown for the monocrops of each crop and for the intercrops with the highest and lowest share of each component species (wheat–pea share (%:%): 75:25 and 12.5:87.5; visible trends are also representative for intercrops laying between these ratios. In 2011, the plant height for both sowing times of wheat was generally higher with a higher wheat share in intercrops (Figure 3A,C), whereas in 2013, the plant height of wheat was higher with a lower wheat share in intercrops in the autumn-sown treatments and also late in the season for spring-sown treatments (Figure 3E,G).

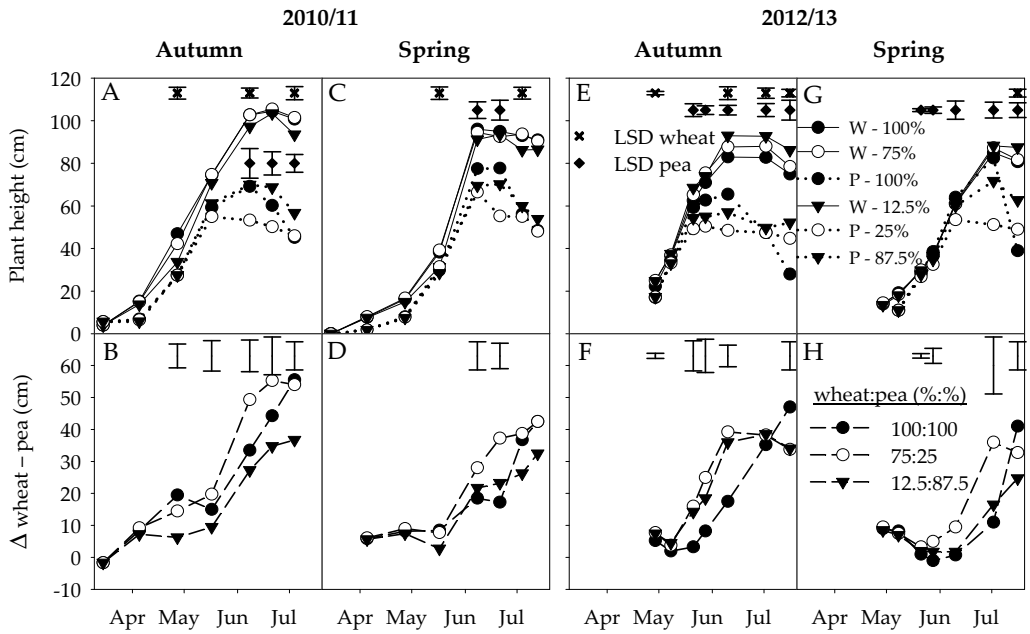


Figure 3. Plant height of autumn- and spring-sown wheat (W) and pea (P) plants and the difference (Δ) in wheat minus pea plants in monocrops (100%) and intercrops with a wheat–pea share (%) of 75:25 and 12.5:87.5 in 2010/11 (**A**–**D**) and 2012/13 (**E**–**H**). Error bars are LSDs for ST × SR interactions ($p < 0.05$).

Pea plant height was higher with 100% and 87.5% pea plants than with 25% pea plants with both sowing times in 2010/11 up to early June before crop stands with a high pea share started to decline until harvest (Figure 3A,C). In 2013, pea plant height was highest with 100% pea plants, closely followed by 87.5% pea plants up to early June in autumn-sown treatments and up to first half of July in spring-sown treatments before decline started. At final harvest, 100% pea plants had the lowest plant height (Figure 3E,G).

The difference (Δ) in the plant height between both crops (Δ in wheat minus pea) showed that wheat grew considerably higher than pea plants with progressing vegetative period, especially in autumn-sown treatments and in the first experimental year (Figure 3B,F). In spring-sown treatments up to the end of May 2011 and up to early June 2013, there were few or no differences between wheat and pea plants (Figure 3D,H). In 2011, the Δ between wheat and pea plants was highest in intercrops with the highest wheat share in autumn-sown treatments from early May on and for spring-sown treatments in June, because in these intercrops, pea crop height was starting to be suppressed by wheat competition. In 2013, the Δ was also higher for intercrops with 75% wheat and 25% pea plants than for monocrops from mid-May until June (autumn-sowing) or early July (spring-sowing) due to the increased wheat plant height with lower wheat share and lower height of pea plants with higher wheat competition. For both years and both sowing times, the Δ between monocrops of wheat and pea plants increased as ripening progressed (from mid to the end of June onwards), and senescence of pea plants resulted in lodging. In 2013, this resulted in the largest difference between wheat and pea plants at harvest.

3.3. Soil Coverage

Soil was covered faster by wheat–pea intercrops and monocrops in 2010/11 (Figure 4A,B) than in 2012/13 (Figure 4C,D). Soil coverage in both years was generally higher with a higher share of wheat than pea plants in the intercrops until end of April for autumn-sown crops and until mid-May for spring sown crops (with a higher spread between treatments in 2010/11). Subsequently, differences between intercrops declined in 2010/11. Contrary to that, impaired crop growth of wheat in 2012/13 starting at the end of April (SD 3–4, cf. Table 2) resulted

in higher soil coverage of intercrops with a higher share of pea plants. For spring-sown intercrops, it took until the end of May in both years to reach the same soil coverage as autumn-sown intercrops.

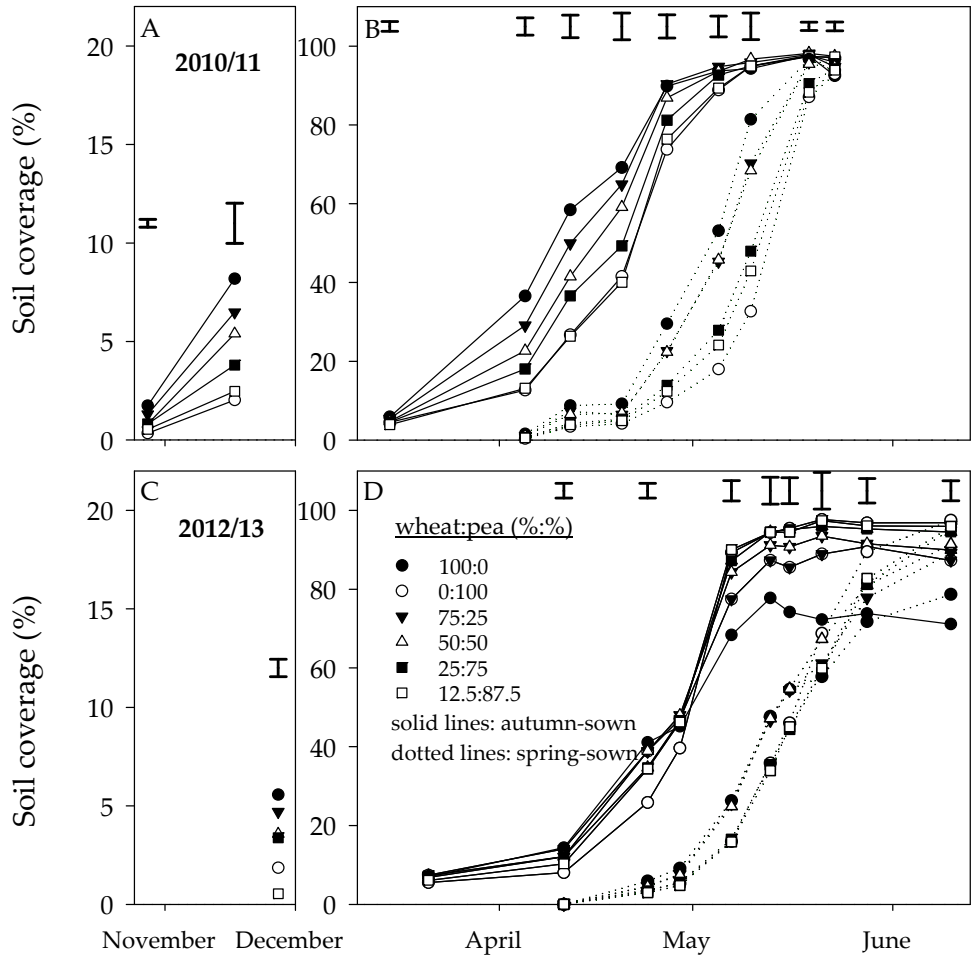


Figure 4. Soil coverage (%) of wheat and pea plants as affected by sowing time and sowing ratio in 2010/11 (**A**,**B**) and 2012/13 (**C**,**D**). Error bars are LSDs for ST × SR interactions ($p < 0.05$).

3.4. Crop Growth Rate

The crop growth rate (CGR) of wheat (Figure 5A–J) increased in both years until early June (SD 5) and subsequently decreased. The CGR was higher for autumn-sown wheat than for spring-sown wheat up to mid-May (SD 4) in both years, with no or few differences between sowing times thereafter.

The CGR of wheat was generally higher, with a higher wheat share up to harvest in 2012/13, whereas in 2010/11, the CGR between mid-May and early June (SD 4–5) was only lower in the intercrops with 12.5% wheat than in the other treatments (Figure 5D) and lowest from SD 5 until final harvest in early July in wheat monocrops (n. s.; Figure 5E). Differences in the CGR between sowing ratios decreased with time, partly even disappearing. For example, the CGR of 25% wheat compared to 100% wheat between early April and the end of April (SD 2–3) was at 26% (2010/11; Figure 5B) or 28% (2012/13; Figure 5G); thus, the shares of CGRs were comparable to their sowing ratios, whereas between mid-May and early June (SD 4–5), the share of 25% wheat compared to 100% wheat was 81% (2010/11; Figure 5D) or 56% (2012/13; Figure 5I), respectively (means over both sowing times).

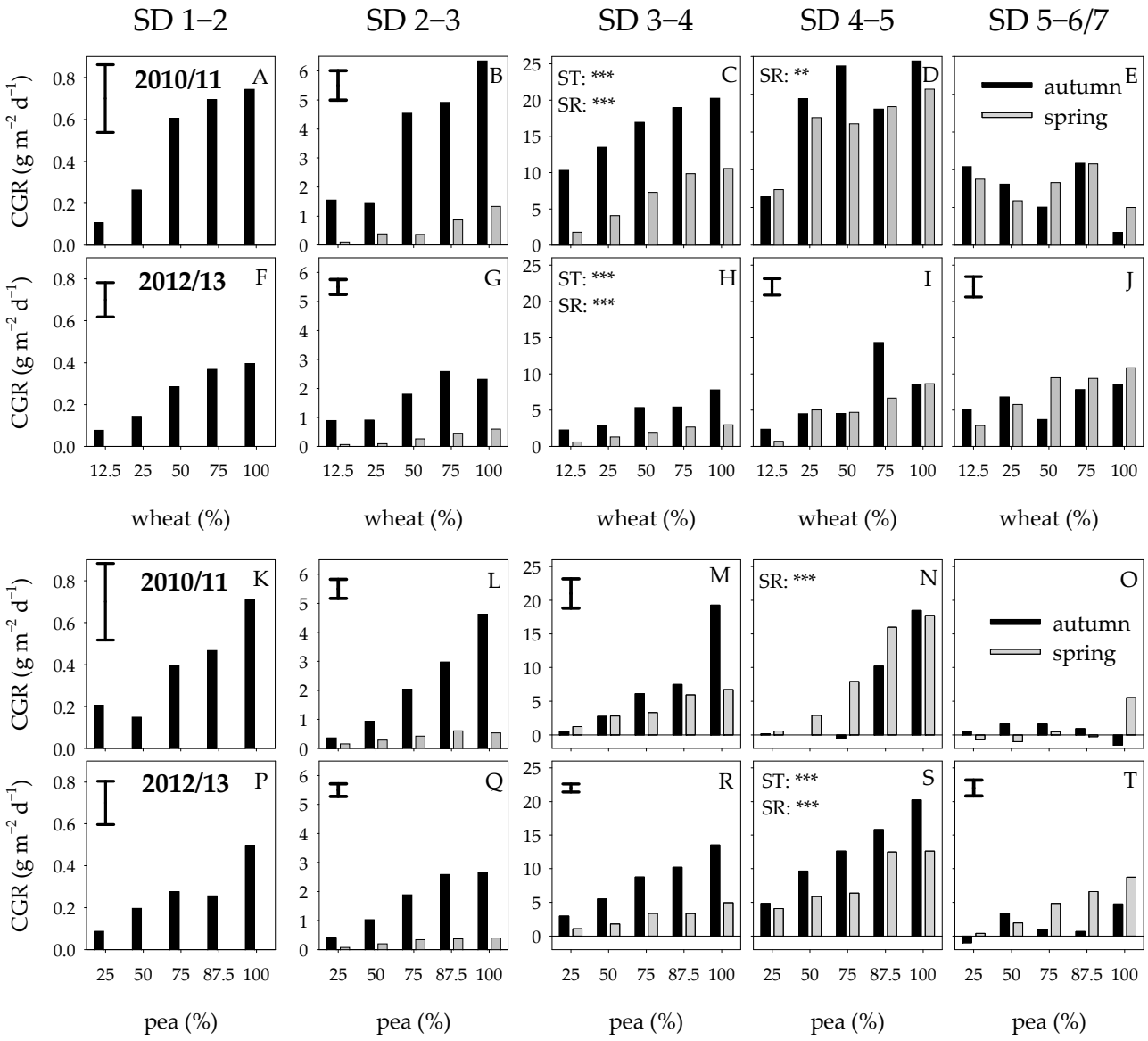


Figure 5. Crop growth rate (CGR) of wheat ((**A**–**E**): 2010/11; (**F**–**J**): 2012/13) and pea plants ((**K**–**O**): 2010/11; (**P**–**T**): 2012/13) as affected by sowing times (STs) and sowing ratio (SR). Sampling dates (SDs) are summarized in Table 1. Asterisks indicate significant differences of main effects at $p < 0.01$ (**) and $p < 0.001$ (***). Error bars are LSDs for ST × SR interactions ($p < 0.05$).

The CGR of pea plants (Figure 5K–T) increased in both years until early June (SD 5) and subsequently decreased. Autumn-sowing as compared to spring-sowing resulted in a higher CGR of treatments with a higher pea plant share up to the end of April (SD 3) and of the pea monocrop up to mid-May (SD 4) in 2010/11; in 2012/13, autumn-sowing had a higher CGR even up to early June (SD 5). For spring-sown pea plants, the CGR was highest between mid-May and early June in both years (SD 4–5). The CGR did not differ between sowing times after mid-May (SD 4) in 2010/11, whereas in 2012/13, the CGR of autumn-sown pea plants was higher between mid-May and early June (SD 4–5), and that of spring-sown treatments with >75% pea plants was higher between early June (SD 5) and final harvest. The CGR decreased with a lower pea share from mid-May to early June (SD 4–5) with no differences between sowing times in 2010/11 (Figure 5N) and a higher CGR of autumn-sown treatments in 2012/13 (Figure 5S). From early June (SD 5) until harvest, sowing date and intercropping ratio had no effect on the CGR (Figure 5O,T). Contrary to the CGR of wheat, the differences in the CGR of pea plants between sowing

ratios stayed high throughout the vegetative period up to early June (SD 5), especially in 2010/11. For example, the CGR of 25% pea plants compared to 100% pea plants between early April and the end of April (SD 2–3) was 20% (2010/11; Figure 5L) or 19% (2012/13; Figure 5Q), whereas between mid-May and early June (SD 4–5), the share of 25% pea plants compared to 100% pea plants was at 2% (2010/11; Figure 5N) or 28% (2012/13; Figure 5S), respectively (means over both sowing times).

Both crops, especially between early April and the end of April (SD 2–3), showed a higher CGR with a higher individual crop share in autumn-sown compared to spring-sown treatments (Figure 5B,G,L,Q).

Comparing sowing times of the monocrops, the CGR of wheat was higher in both years with autumn-sowing compared to spring-sowing from early April to mid-May (SD 2–4). The CGR of pea plants with autumn-sowing compared to spring-sowing was higher from early April to mid-May (SD 2–4) in 2010/11 and from early April to early June (SD 2–5) in 2012/13.

The total CGR (Table 2) was highest over both sowing times and all four intercropping ratios in both years between mid-May and early June (SD 4–5) (except for monocrops of wheat in 2012/13). The second-highest CGR was observed from the end of April to mid-May (SD 3–4) for all treatments in 2010/11 and treatments with 87.5% and 100% pea plants in 2012/13, whereas in 2012/13, treatments with 25% to 100% wheat had a higher CGR between early June and harvest (SD 5–6/7) than between the end of April and mid-May (SD 3–4). The lowest total CGR occurred at early growth up to early April (SD 1–2) in both years, followed by the CGR from early April to the of April (SD 2–3) for spring-sown treatments in 2010/11 and autumn-sown ones in 2012/13 or the CGR from early June (SD 5) up to harvest for autumn-sown treatments in 2010/11.

The total CGR was higher with autumn- than with spring-sowing up to mid-May (SD 4) in 2010/11 and up to early June (SD 5) in 2012/13. Subsequently, no differences were found between sowing times in 2010/11, whereas spring-sown treatments had a higher total CGR from early June (SD 5) up to harvest in 2012/13.

Differences for sowing ratios were observed between early April and the end of April (SD 2–3) in 2010/11 and from the end of April to early June (SD 3–5) in 2012/13. Between early April and the end of April (SD 2–3) in 2010/11, a SD × SR interaction occurred: 100% wheat had the highest total CGR at both ST and the lowest CGR had intercrops with 25% wheat and 75% pea plants in autumn-sown treatments and 100% pea plants in spring-sown treatments. Between the end of April and mid-May (SD 3–4) in 2012/13, a SD × SR interaction occurred: in autumn-sown treatments, a higher total CGR was observed for 100% pea plants, and the lowest CGR was observed for 100% wheat and intercrops with 75% wheat and 25% pea plants. In spring-sown treatments, the total CGR of 100% pea plants and all intercrops was higher than that of 100% wheat. Between mid-May and early June (SD 4–5) in 2012/13, 100% pea plants and intercrops with 12.5% wheat and 87.5% pea plants had the highest CGR, and 100% wheat had the lowest.

3.5. Relative Growth Rate

The relative growth rate (RGR) of both crops was generally highest in both years between early April and the end of April (SD 2–3) for autumn-sown treatments and between the end of April to mid-May (SD 3–4) for spring-sown treatments, thus during stem elongation of both crops. The RGR decreased afterwards during crop growth with the generally lowest values between early June (SD 5) and final harvest (Figure 6).

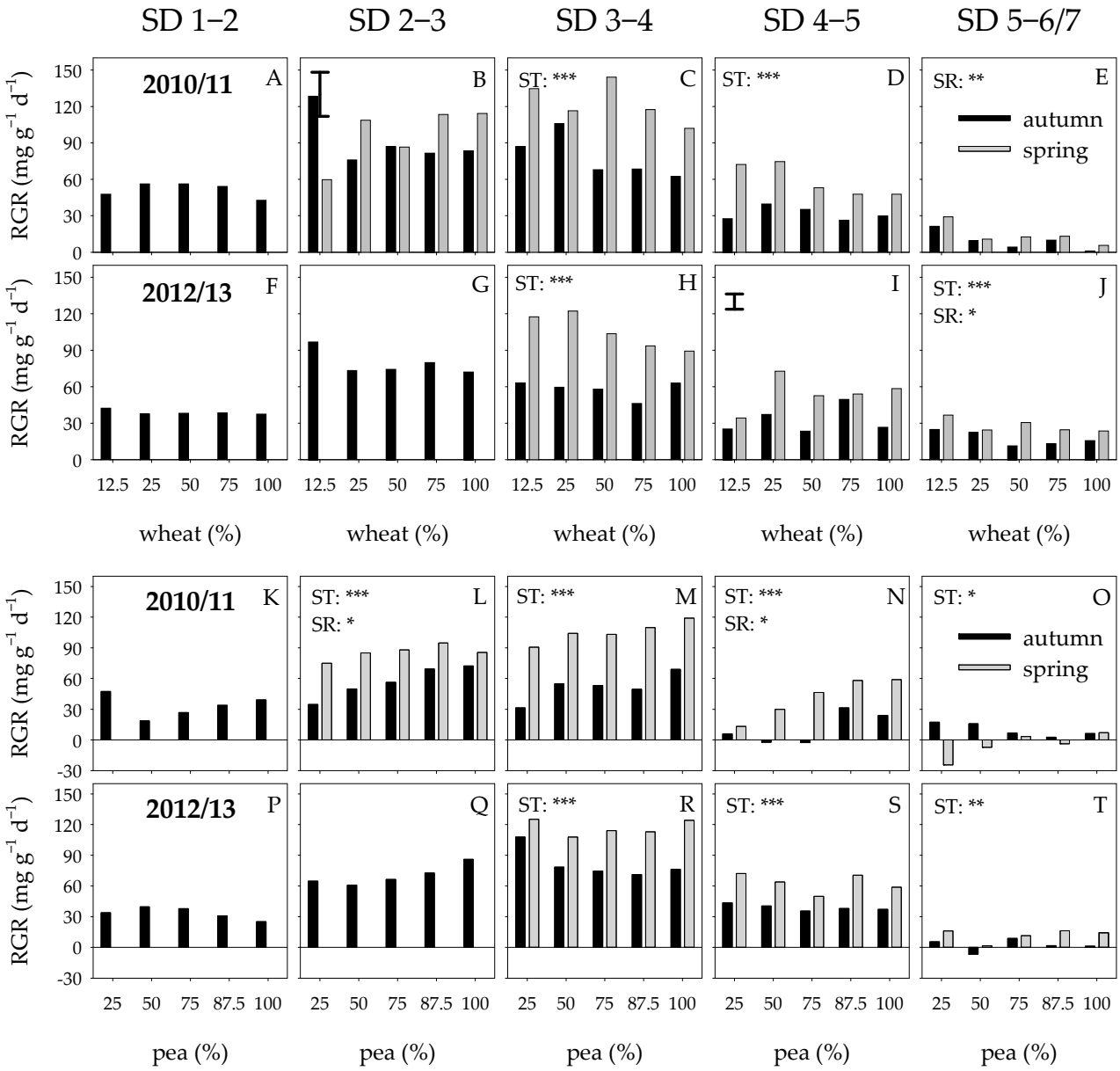


Figure 6. Relative growth rate (RGR) of wheat ((**A**–**E**): 2010/11; (**F**–**J**): 2012/13) and pea plants ((**K**–**O**): 2010/11; (**P**–**T**): 2012/13) as affected by sowing time (ST) and sowing ratio (SR). Sampling dates (SDs) are summarized in Table 1. Asterisks indicate significant differences of main effects at $p < 0.05$ (*), $p < 0.01$ (**) and $p < 0.001$ (***). Error bars are LSDs for ST × SR interactions ($p < 0.05$).

The RGR of wheat in 2010/11 tended to be higher with decreasing shares in the intercrops from the end of April (SD 3) in 2010/11 (n. s.; Figure 6C–E) and between the end of April and mid-May (SD 3–4) in 2012/13 (especially for spring-sown wheat; n. s.; Figure 6H). From early June (SD 5) until harvest, the CGR of 12.5% wheat in both years was higher than in the other treatments (with 25% wheat showing intermediate values in 2012/13) (Figure 6E,J). The RGR of spring wheat was higher than that of winter wheat between the end of April and early June (SD 3–5) in 2010/11 and between the end of April to mid-May (SD 3–4) and early June (SD 5) to harvest in 2012/13 (Figure 6C,D,H,J).

The RGR of pea plants was highest from early April to mid-May (SD 2–4) in both years (Figure 6L,M,Q,R). Subsequently, the RGR decreased during crop growth with the lowest and partly negative values between early June (SD 5) and final harvest. The RGR significantly decreased with a lower pea share of the sowing ratio between early April and the end of April (SD 2–3) and mid-May and early June (SD 4–5) in 2010/11 (Figure 6L,N).

There was also the same tendency between the end of April and mid-May (SD 3–4) in 2010/11 (n. s.; Figure 6M). Contrary to that, the RGR of pea plants was not affected by the sowing ratio in 2012/13 (Figure 6P–T).

The total RGR (Table 2) was highest from early April to mid-May (SD 2–4) in 2010/11 and from the end of April to mid-May (SD 3–4) in 2012/13. The total RGR was not recorded for spring-sown treatments between mid-March and early April (SD 1–2) in 2010/11 and between mid-March and the end of April (SD 1–3) in 2012/13; for all other sampling periods, the total RGR was higher with spring- than with autumn-sowing (with no differences from early June (SD 5) until harvest in 2010/11). The total RGR was highest with wheat monocrops and lowest with pea monocrops and decreased with lower wheat and higher pea share between early April and the end of April (SD 2–3) in 2010/11 and from early June (SD 5) until harvest in 2012/13; a reverse pattern was observed between mid-May and early June (SD 4–5) in 2012/13.

Table 2. Total crop growth rate and total relative growth rate of crop stands as affected by sowing time and sowing ratio.

	SD [1] 1–2		SD 2–3		SD 3–4		SD 4–5		SD 5–6/7	
Year [2]	2011	2013	2011	2013	2011	2013	2011	2013	2011	2013
					Crop growth rate (g m^{-2} d^{-1})					
Sowing time (ST)										
Autumn	0.73	0.43	4.97^{a}	1.69	19.4^{a}	10.8^{a}	20.8	16.3^{a}	−0.33	6.89^{b}
Spring	–	–	0.86^{b}	–	9.0^{b}	4.1^{b}	20.0	11.2^{b}	1.16	10.2^{a}
Sowing ratio (SR; %) (wheat:pea)										
100:0	0.74	0.40	3.85^{a}	1.47	15.4	5.42^{d}	22.6	8.6^{c}	−1.20	9.73
75:25	0.90	0.46	3.17^{b}	1.79	15.3	6.12^{cd}	18.6	15.0^{ab}	1.87	8.37
50:50	0.76	0.49	3.08^{b}	1.68	14.9	7.37^{bc}	21.4	12.4^{b}	−0.05	9.29
25:75	0.66	0.42	2.16^{c}	1.64	13.5	8.18^{ab}	21.9	14.3^{ab}	1.37	9.29
12.5:87.5	0.58	0.34	2.64^{bc}	1.99	12.8	8.27^{ab}	20.0	15.7^{a}	1.26	7.80
0:100	0.71	0.50	2.59^{bc}	1.55	13.0	9.25^{a}	18.1	16.4^{a}	−0.72	6.76
ANOVA										
ST			***		***	***		***		***
SR			***			***		***		
ST × SR			*			*				
					Relative growth rate (mg g^{-1} d^{-1})					
Sowing time (ST)										
Autumn	41.6	34.5	75.2^{b}	74.6	67.9^{b}	70.0^{b}	27.7	35.8^{b}	6.6	9.7^{b}
Spring	–	–	96.6^{a}	–	113.8^{a}	108.9^{a}	54.9	60.0^{a}	9.1	19.8^{a}
Sowing ratio (SR; %) (wheat:pea)										
100:0	43.2	37.8	99.2^{a}	72.5	82.5	76.6^{d}	39.1	42.9	3.7	20.0^{a}
75:25	39.1	36.9	89.6^{ab}	76.3	89.5	79.0^{cd}	35.7	53.0	11.3	14.5^{bc}
50:50	52.8	37.6	81.3^{b}	70.4	96.8	87.1^{bc}	39.7	46.2	7.7	16.0^{b}
25:75	42.4	32.7	82.5^{b}	73.4	90.9	94.4^{ab}	47.8	46.2	8.6	14.7^{bc}
12.5:87.5	35.5	28.1	83.9^{b}	90.1	91.3	90.2^{b}	44.1	51.0	11.1	12.4^{cd}
0:100	36.6	33.9	78.8^{b}	64.7	94.0	100.2^{a}	41.4	47.9	4.7	10.8^{d}
ANOVA										
ST			***		***	***	***	***		***
SR			*			***				***
ST × SR										

[1] Sampling dates (SDs) are summarized in Table 1; [2] 2011 = 2010/11, 2013 = 2012/13. Different letters indicate significant differences at $p < 0.05$ (*) and $p < 0.001$ (***).

3.6. Above-Ground Dry Matter of Wheat and Pea Plants

The above-ground dry matter (AGDM) of wheat and pea plants depending on sowing time and sowing ratio is shown in Figure 7. Wheat monocrops produced more AGDM than pea monocrops in 2010/11, with +31% for autumn-sowing and +19% for spring-sowing, whereas pure pea plants produced more AGDM than wheat monocrops in 2012/13, with

+33% for autumn-sowing and +3% for spring-sowing. A comparison of sowing times for individual sole crop stands showed +32% for wheat and +20% for pea plants in 2010/11 and −4% for wheat and +24% for pea in in 2012/13 with autumn-sowing compared to spring-sowing.

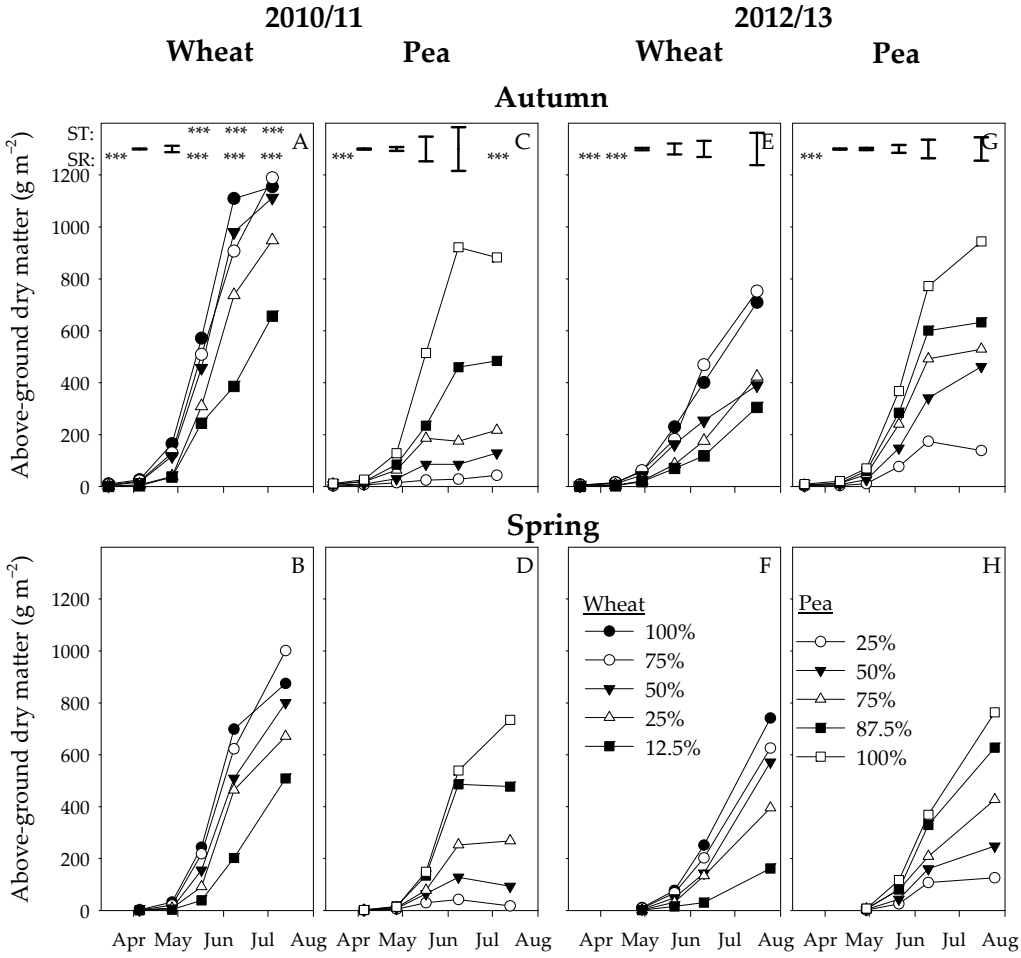


Figure 7. Above-ground dry matter of autumn- and spring-sown wheat and pea plants in 2010/11 (**A**–**D**) and 2012/13 (**E**–**H**) depending on sowing time (ST) and sowing ratio (SR). Asterisks indicate significant differences of main effects at $p < 0.001$ (***). Error bars are LSDs for ST × SR interactions ($p < 0.05$). Asterisks and error bars are valid for the graph where they are shown, plus the graph below.

For both crops, the AGDM of intercrops generally corresponded to their sowing ratios during early growth (i.e., during March for autumn-sown crop stands and during April for spring-sown intercrops). Later on, considerable deviations in the production of ADGM in relation to their sowing ratios started in April for autumn-sown intercrops and May for spring-grown intercrops.

Considering both sowing times in both years, based on the comparison with the wheat biomass in monocrops, the wheat biomass in the intercrops increased relative to their share of the sowing ratio (Figure 7A,B,E,F). The increase was much higher in 2010/11 than in 2012/13 (except for the autumn-sown intercrop with 75% wheat share). At harvest, the share of the wheat intercrops on the AGDM of pure-sown wheat for the sowing ratios with 12.5%, 25%, 50% or 75% for autumn-sown wheat was 57%, 82%, 96% and 103% in 2010/11 (Figure 7A) and 43%, 60%, 55% and 106% in 2012/13 (Figure 7E), respectively, while for spring-sown wheat, it was 58%, 77%, 92% and 114% in 2010/11 (Figure 7B) and 22%, 53%, 77% and 84% in 2012/13 (Figure 7D), respectively.

In contrast, the AGDM of pea plants (Figure 7C,D,G,H) in the intercrops decreased relative to their share, when compared to the pea monocrops at both sowing times in both years. The decrease was much higher in 2010/11 than in 2012/13. At harvest, the share of the pea intercrops of the AGDM of pea monocrops for the sowing ratios with 25%, 50%, 75% or 87.5% for autumn-sown pea plants was 5%, 15%, 25% and 55% in 2010/11 (Figure 7C) and 15%, 49%, 56% and 67% in 2012/13 (Figure 7G), respectively, while for spring-sown pea plants, it was 2%, 13%, 37% and 65% in 2010/11 (Figure 7D) and 17%, 32%, 56% and 82% in 2012/13 (Figure 7G), respectively.

3.7. Above-Ground Dry Matter of Crop Stands

The AGDM of crop stands depending on sowing time and sowing ratio is shown in Figure 8. At harvest, the AGDM over all crop stands was 23% higher in 2010/11, with 1022 g m^{-2}, than in 2012/13, with 831 g m^{-2}. The mean AGDM of autumn-sown or spring-sown crop stands was higher in 2010/11 compared to 2012/13 by 29% (1136 vs. 881 g m^{-2}) or 16% (908 vs. 781 g m^{-2}). Between sowing times, the mean yield over crop stands at harvest was 25% (2010/11) or 13% (2012/13) higher with autumn-sowing compared to spring-sowing. In both years, autumn-sown crop stands had a higher AGDM than spring-sown crop stands during the whole vegetation period.

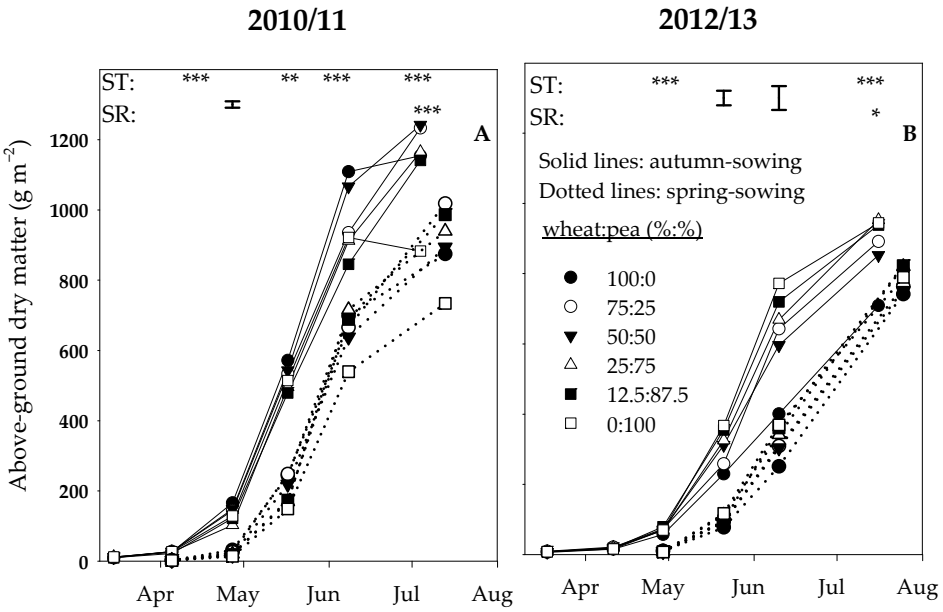


Figure 8. Above-ground dry matter of autumn- and spring-sown crop stands of monocrops of wheat and pea plants and wheat–pea intercrops in 2010/11 (**A**) and 2012/13 (**B**) depending on sowing time (ST) and sowing ratio (SR). Asterisks indicate significant differences of main effects at $p < 0.05$ (*), $p < 0.01$ (**) and $p < 0.001$ (***). Error bars are LSDs for ST × SR interactions ($p < 0.05$).

In 2010/11, the AGDM of autumn-sown crop stands did not differ from mid-March to early April, while by the end of April, they ranked as follows: 100:0 ≥ 50:50, 75:25 ≥ 0:100 ≥ 12.5:87.5 ≥ 25:75. In contrast, the AGDM of spring-sown crop stands did not differ. By mid-May, the crop stands over both sowing times ranked as follows: 100:0 ≥ 75:25, 50:50 ≥ 25:75, 0:100, 12.5:87.5. In early June, the AGDM did not differ between crop stands. At final harvest, the AGDM in wheat monocrops and all intercrops was higher than in pea monocrops (for both sowing times) (Figure 8A).

In 2012/13, the AGDM of autumn-sown crop stands did not differ from mid-March to the end of April, but they ranked in mid-May as follows: 0:100 ≥ 12.5:87.5 ≥ 25:75, 50:50 > 75:25, 100:0. In contrast, the AGDM of spring-sown crop stands again did not differ. By early June, the autumn-sown crop stands were ranked as follows: 0:100 ≥ 12.5:87.5

≥ 25:75, 75:25 ≥ 50:50 > 100:0. Meanwhile, the spring-sown crop stands were ranked as follows: 0:100, 12.5:87.5, 25:75 ≥ 75:25, 50:50 ≥ 100:0. At final harvest, the AGDM in pea monocrops and all intercrops was higher than in wheat monocrops for both sowing times (Figure 8B).

3.8. Partial and Total Land Equivalent Ratios

The partial land equivalent ratios (LERs) of wheat or pea plants and the total LER are shown in Figure 9 for the main effects of sowing time and sowing ratio.

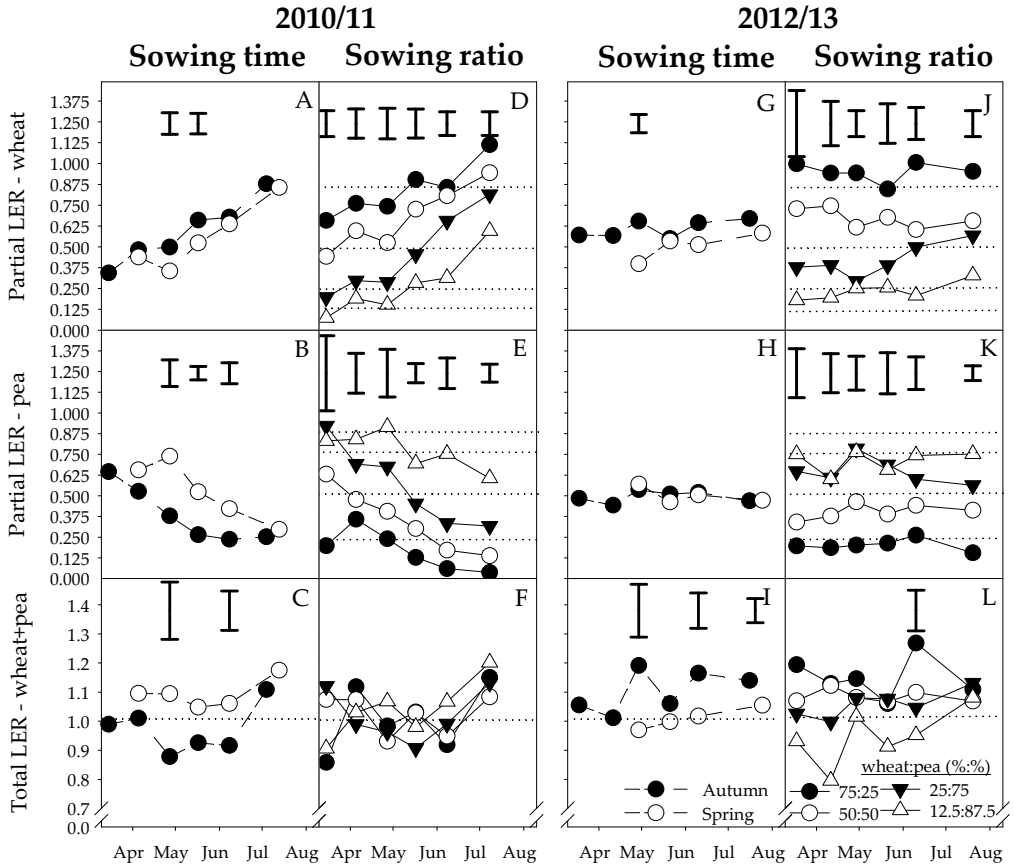


Figure 9. Partial LER of wheat (**A**,**D**,**G**,**J**) and pea plants (**B**,**E**,**H**,**K**) and total LER of wheat–pea intercrops (**C**,**F**,**I**,**L**) for the main factors of sowing time in 2010/11 and 2012/13 and sowing ratio in 2010/11 and 2012/13. Error bars are LSDs ($p < 0.05$). As the final harvest occurred on different dates for autumn and spring-sown treatments, a mean value between the harvest dates was chosen to show the effects of sowing ratio. Dotted lines in (**D**,**J**) show the partial LER levels of 0.125, 0.25, 0.5 and 0.75, indicating the sowing ratios of wheat in intercrops (12.5%, 25%, 50% and 75%), while in (**E**,**K**), they show the partial LER levels of 0.25, 0.50, 0.75 and 0.875, indicating the sowing ratios of pea plants in intercrops (25%, 50%, 75% and 87.5%) and in (**C**,**F**,**I**,**L**), they show the LER = 1.0 line for the wheat–pea intercrops.

In 2010/11, the partial LER of wheat increased over time, while the partial LER of pea plants decreased over time. With autumn-sowing, the partial LER of wheat was higher at the end of April (SD 3) and in mid-May (SD 4) (Figure 9A), while that of pea plants was lower from the end of April to early June (SD 3–5) than with spring-sowing (Figure 9B). Up to the end of April (SD 3), the partial LER of wheat corresponded to the sowing ratio of wheat in the intercrops. From that time until harvest, the partial LER of wheat constantly increased, especially in the treatments with a lower share of wheat. With a wheat share of 12.5, 25, 50 or 75%, a partial LER of 0.60, 0.81, 0.95 or 1.11 was observed at final harvest (Figure 9D). In contrast, the partial LER of pea plants constantly decreased from the end of

April until harvest, especially in treatments with a lower pea share; thus, a pea share of 25, 50, 75 or 87.5% resulted in a partial LER of 0.04, 0.14, 0.32 or 0.61 at harvest (Figure 9E).

In 2012/13, the partial LER of wheat at the end of April (SD 3) was higher with autumn-sowing than with spring-sowing (Figure 9G), whereas the partial LER of pea plants did not differ between sowing times (Figure 9H). The partial LER of wheat and pea plants stayed relatively constant over time for intercrops with 50% and 75% wheat share, while it increased for intercrops with 12.5 and 25% of wheat until harvest. With a wheat share of 12.5, 25, 50 or 75%, a partial LER of 0.33, 0.57, 0.66 or 0.95 was observed at harvest (Figure 9J). The partial LER of pea plants was relatively constant over time and throughout the vegetative period for all intercrops below its share on the sowing ratio. The final partial LER of pea plants at harvest for each pea share of 25, 50, 75 or 87.5% was 0.16, 0.41, 0.56 or 0.75 (Figure 9K).

In 2010/11, the total LER during the vegetative period for autumn-sown intercrops was <1 between the end of April and early June (SD 3–5), but for spring-sown intercrops, it was >1 throughout the vegetative period (except for the final harvest date), with significantly higher values for autumn-sowing at the end of April (SD 3) and in early June (SD 5) (Figure 9C). The total LER of intercrops fluctuated around 1 for all intercrops during the vegetative period but was >1 for all intercrops at final harvest (Figure 9F). In contrast, in 2012/13, the total LER was always > 1, except for autumn-sown intercrops up to mid-May (SD 4). Autumn-sown intercrops had significantly higher values at the end of April (SD 3), in early June (SD 5) and at harvest, with a mean of 1.14 or 1.06 with autumn- or spring sowing (Figure 9I). Among sowing ratios, the total LER was always >1, except for the 25%:75% intercrops in mid-May (SD 4) and the 12.5%:87.5% intercrops up to early June (SD 5) (Figure 9L).

At final harvest, the total LER for all intercrops was >1 with a mean over both sowing times and all four intercropping ratios of 1.14 in 2010/11 and 1.10 in 2012/13.

4. Discussion

4.1. Crop Development

Compared to spring-sowing, autumn-sowing resulted in earlier initiation and longer duration of development stages and in earlier maturation as already observed for wheat [7] and pea plants [9] in monocrops. Thus, the critical stages of yield component formation and ripening last longer and start earlier, before the onset of dry summer conditions.

4.2. Plant Height

Plant height of individual crops differed between years and sowing times as plant height changes with photoperiod, temperature and precipitation [27]. Furthermore, the sowing ratio affected the height of individual crops on some dates: with its lowest sowing ratio, wheat was smallest in 2011 but tallest in 2013 on several dates, whereas the height of pea plants in crop stands was generally reduced during crop growth due to competition with wheat. In contrast, Bedoussac and Justes [17] observed no significant difference between sole crop and intercrop canopy height for both wheat and pea plants at any development stage. Contrary to our observations, Fernández-Aparicio et al. [28] reported that pea plants were higher in intercrops with different cereals due to an increase in internode length.

Haymes and Lee [20] have shown that plant height plays an important role in competition between crops, with taller cultivars having a competitive advantage. Additionally, shading by one crop towards the other affects nutrient uptake as shown for calcium by Morris and Garrity [29]. Also, pea plants as the suppressed partner in oat–pea intercrops had a lower concentration of Ca and K in crop residues, whereas oat as a dominant partner

had higher concentrations of Ca, Cu, K, Mg, Mn and Zn in the crop residues in intercrops with a low oat share [30,31]. Plant height of pea monocrops strongly decreased towards harvest time compared to pea plants in intercrops that were supported by the accompanying wheat. Thus, a main objective of intercropping, the prevention of lodging of pea plants at harvest, could be obtained as observed by Bedoussac and Justes [17] and Podgórska-Lesiak and Sobkowicz [32].

4.3. Soil Coverage

Higher and faster soil coverage was achieved with autumn-sowing and with a higher share of wheat in the sowing ratio. Thus, intercropping can support indirect weed control. As pea plants are subjected to weed infestation due to their slow early development, adding a cereal partner may result in faster shading and thereby weed suppression as shown for spring-sown intercrops of pea plants with barley [33] or oats [34,35]. Also, for winter faba beans, a considerably lower soil coverage over winter and in early spring has been observed in Eastern Austria compared to winter wheat, especially when winter kill was high [9,12]. Consequently, intercropping might especially be important for suppressing weeds in more legume-based intercrops and also with autumn-sowing. In any case, soil coverage over winter is also strongly affected by sowing date in autumn as shown for winter poppies in Eastern Austria [36].

Furthermore, soil coverage through faster leaf area development during early growth reduces soil evaporation [37], increases radiation interception, cushions the impact of raindrops and thus reduces erosion processes [38]. Consequently, adding wheat to pea plants in intercrops might decrease unproductive water loss through evaporation and increase soil protection against the impact of raindrops especially with autumn-sowing.

4.4. Crop Growth Rate

The CGR of wheat was generally highest between the development stages of flag leaf stage/booting and fruit development, with no differences between sowing times. As the crop development of SW was delayed compared to WW by some weeks, so too was the CGR peak.

The temporal course and height of CGR and RGR over time differ between crops and are affected by weather conditions [39,40]. The resulting growth complementarity over time, with a higher growth rate of wheat until pea flowering and then of pea plants until wheat flowering, can be an advantage of intercropping [17]. We observed a higher CGR of wheat than of pea plants in intercrops during early growth (up to the end of April) in 2010/11, which resulted in out-competition of pea plants by wheat until harvest. The higher CGR of wheat compared to pea plants remained during the vegetative period. Bedoussac and Justes [17] have already shown for wheat–pea intercrops that early taller crops and faster growth of wheat reduced light absorption and consequently biomass production of pea plants. During early growth, cereals take up soil mineral N faster than legumes, as shown for barley–pea intercrops [41]. The competitiveness of cereals further increases with higher N supply, as shown for oat–pea intercrops [2].

Conversely, in 2012/13, the CGR of wheat was at the start of the vegetative period stronger impaired than that of pea plants, presumably due to cold conditions, which might have limited N mineralization and thereby N supply. Subsequently, the CGR of pea plants was until early June higher than that of wheat. In contrast, pea plants might have benefitted from of N_2 fixation, which can compensate for the N limitation in the soil when low N mineralization occurs [42].

4.5. Relative Growth Rate

The RGR was highest for both crops around stem elongation and decreased afterwards. This decrease with time is due to the increase in the share of non-assimilatory tissues [43]. The increase in the RGR of wheat with lower sowing ratio from the end of April onwards in 2010/11 (n. s.) and of wheat in 12.5%:87.5% intercrops from early June onwards in both years may be explained by more resources for single plants, e.g., of soil mineral N or light. Whaley et al. [44] have reported that the RGR increased in wheat monocrops with a lower plant density as single shoots absorbed more radiation. However, the RGR of pea plants was much lower with a lower pea share in April and from the end of May to early June in 2010/11, which might be explained by resource limitation, e.g., for light, through the dominant cereal partner. In the second experimental year, the RGR of both crops was not affected by sowing ratio, indicating lower competition between crops than in the first year.

4.6. Above-Ground Biomass and Land Equivalent Ratio

Higher AGDM yields of autumn-sown intercrops were a result of a longer time for biomass formation, as the development stages lasted longer as shown for wheat and pea plants, resulting in a better formation of yield components as shown under Pannonian climate conditions for faba beans [9,45], peas [46], triticale [8] and wheat [7,47]. Also, the seed yield of winter poppies under Pannonian climate conditions was considerably higher than values reported for spring poppies [36].

Wheat monocrops produced more AGDM in 2010/11 than pea monocrops and were consequently also the much stronger partner in intercrops as indicated by increasing partial LERs of wheat and decreasing partial LERs of pea plants over time, especially in intercrops with a low wheat and a high pea share. In contrast, in 2012/13, pea monocrops had a higher AGDM with autumn-sowing and a similar AGDM with spring-sowing compared to wheat monocrops. In the intercrops, this resulted in low competition of wheat towards pea plants, which is indicated by constant partial LERs of wheat with 50 and 75% wheat share and less increased partial LERs of wheat with 12.5 and 25% wheat share in 2012/13 than in 2010/11 and just slightly impaired partial LERs of pea plants over time. Similar to these observations, differences in plant height between wheat and pea plants were lower in 2012/13 than in 2010/11.

The total AGDM at harvest was highest in wheat monocrops and intercrops in 2010/11 and pea monocrops and intercrops in 2012/13. This resulted in LERs of all intercrops of >1 in both years with no statistical differences between intercrops. The mean LER over both sowing times and all four intercropping ratios of 1.14 in 2010/11 and 1.10 in 2012/13 showed a yield advantage for AGDM production of intercrops over monocrops of 14% or 10%. Intercropping benefits could be used much more with autumn-sowing compared to spring-sowing in 2012/13, as the higher total LERs at harvest showed. Similar to our observations, autumn- and spring-sowing of wheat–faba bean intercrops in England also resulted in yield increases over monocrops, with wheat always contributing more strongly to the total grain yield [20]. Also, in spring-sown barley–pea intercrops in Denmark grown in a replacement design with a 50% sowing ratio of each monocrop, a LER > 1 was obtained, with barley contributing 90% and pea plants just 15% to the intercrops yields. The dominance of barley was attributed to its faster root system growth regarding root depth and root distribution and thereby faster nutrient uptake [48]. Urbatzka et al. [18] reported that intercrops of pea plants with cereals are easier to realize with winter peas compared to spring peas. But their conclusion was based on a comparison of long-strawed winter pea varieties with a pronounced indeterminate growth and large stem biomass intercropped with winter rye and of spring peas intercropped with spring oats, where winter peas achieved a higher grain yield in intercrops than in the monocrops as the accompanying

cereal partner improved lodging resistance. However, spring pea yields were relatively low due to the dominance of oats. Contrary to that, there were no differences in partial LERs of wheat and pea plants between sowing times at harvest in our experiment, showing that the final competition between both crops was not affected by sowing time.

The partial LER of wheat in the intercrops corresponded at early growth in spring to the sowing ratio; an increase in the partial LER of wheat over time over both sowing times and all four intercropping ratios in 2010/11 and for the lower sowing ratios in 2012/13 resulted in wheat becoming the dominant partner in the intercrops. Contrary to our observations, interspecies competition already at early growth determined the final biomass yield of fenugreek–buckwheat intercrops [40] and durum wheat–winter pea intercrops [17].

Values of total LER > 1 at final harvest showed that intercrops could acquire more growth resources (light, water or nutrients) than monocrops [49]. A LER > 1 in buckwheat–fenugreek intercrops was attributed to enhanced N fixation and N uptake in intercropping compared to monocrops [40]. Additionally, intercrops can also achieve a higher LER of the grain N yield, as shown for unfertilized oat–pea intercrops, where the higher grain N yield was attributed to higher grain N concentrations of oats in intercrops [15].

5. Conclusions

Autumn-sowing resulted in earlier development, taller plants, faster soil coverage and more AGDM production than spring-sowing for both wheat and pea crops.

Intercropping resulted in higher soil coverage compared to pea monocrops, a reduced lodging of pea plants at harvest, especially with a higher share of wheat than pea plants in the intercrops, and a higher biomass production over all sowing times and sowing ratios. The final biomass of monocrops reflected their competitive ability in the intercrops. Wheat was the stronger partner, out-competing pea plants especially in the first year. High growth rates of wheat or pea plants in intercrops resulted in a final AGDM of all intercrops similar to that of the better monocrop (wheat in the first and pea plants in the second year) and a higher one than that of the other monocrop. For all intercrops, this resulted in a LER > 1, indicating their high yielding potential. Due to additional ecological advantages of intercropping, an increase in arable land sown with intercrops is highly desirable.

Author Contributions: Conceptualization, R.W.N., H.-P.K. and H.W.; methodology, R.W.N., H.-P.K. and H.W.; software, R.W.N.; validation, G.M.; formal analysis, R.W.N., P.H. and A.B.; investigation, R.W.N., P.H. and A.B.; resources, H.-P.K. and H.W.; writing—original draft preparation, R.W.N.; writing—review and editing, P.H., A.B., H.W., G.M., A.K.-K., J.B., T.L., M.G., E.A., K.K.Z. and H.-P.K.; visualization, R.W.N.; supervision, H.-P.K. and H.W.; project administration, R.W.N.; funding acquisition, H.-P.K. and H.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

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