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Impact of Pea Genotypes on Their Performance in Intercropping With Different Species

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ABSTRACT

Intercropping has been widely proposed as a strategy to improve the sustainability and resilience of agricultural systems. Grain legumes are particularly suited for intercropping due to their functional diversity and capacity for biological nitrogen fixation; however, challenges remain to design efficient intercropping systems centred on the grain legume species. Notably, varietal differences within the legume species may strongly influence competitive interactions and, consequently, intercrop performance. In this study, we evaluated the performance of twelve pea (*Pisum sativum* L.) varieties in pure stands but also intercropped either with barley (*Hordeum vulgare* L.) or lentil (*Lens culinaris* L.). The experiment was conducted during two contrasting growing seasons in small plots in Switzerland. We assessed grain yields of each species, as well as intercropping effects on lodging and disease development. The main results showed that barley was too competitive, but intercropping with lentil allowed to maintain pea yield during a bad year. Intercropping generally provided advantages in terms of yield stability, lodging control, and disease management. Pea–barley intercrops effectively limited lodging and significantly reduced ascochyta blight severity, but barley proved highly competitive, leading to reduced pea yields. In contrast, pea–lentil intercrops allowed peas to maintain yields under unfavourable climatic conditions and led to moderately reduced disease development, although productivity was more variable. Strong varietal effects were observed, and promising pea varieties for intercropping were identified. These results highlight the importance of jointly selecting associated crops and pea varieties to maximize the benefits of intercropping. Optimizing such systems requires an integrated approach that combines varietal choice, sowing density management, and consideration of downstream value-chain opportunities.

1 | Introduction

Legume crops are increasingly important for the development of sustainable agricultural cropping systems. They contribute to local protein supply, thereby reinforcing food security while limiting environmental impacts (Nemecek et al. 2008). From a nutritional point of view, their content in proteins, fibre, and micronutrients makes them high-value products for feed and food (Affrifah et al. 2023). Legumes also offer an economic opportunity to farmers through the diversification of their incomes as well as new products suitable for direct distribution (Reckling et al. 2016).

In agricultural systems, legumes play a crucial role thanks to their ability to fix nitrogen, and therefore can reduce the dependency on mineral nitrogen fertilizers by increasing soil fertility (Peoples et al. 2009). They represent good preceding crops, showing positive impacts on the yield of a subsequent cereal thanks to high nitrogen delivery (Guinet et al. 2020). Thanks to these agronomic benefits and their role in

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diversification of the crop rotation, legume crops contribute to a more sustainable and resilient agriculture (Stagnari et al. 2017; Ferreira et al. 2021).

Despite many agronomic advantages, legumes face several obstacles to their larger adoption. First, legumes tend to have unstable yields due to their sensitivity to abiotic stresses – such as drought or extreme temperatures – but also to diseases, which can require costly treatments (Sinclair and Vadez 2012; Araújo et al. 2015). Grain legumes indeed suffer from a wide range of diseases and pests, especially ascochyta blight in peas, which is caused by a fungus and affects leaves, stems, and pods of peas, ultimately leading to important yield losses (Rubiales and Fondevilla 2012). Control strategies are based primarily on varietal selection, by identifying disease-tolerant varieties and resistance genes, and particularly wide crop rotation (Rubiales et al. 2015). Finally, economically speaking, legumes lack stable outlets: low consumption of legumes in Europe and the lack of agrifood processing are hampering their growth in the market, thus limiting their value and attractiveness to farmers (Mawois et al. 2019). In this context, integrating legumes into existing cropping systems, resulting in crop associations with beneficial side effects on each component and following crops, could be an opportunity to overcome these adoption barriers.

Intercropping, defined as the simultaneous cultivation of several plant species on the same field, is attracting growing interest due to its many agronomic and ecological advantages (Bedoussac et al. 2015). Intercropping relies on positive interactions between crop species, such as facilitation and complementarity, theoretically allowing an increase in productivity by improving resource use efficiency, such as space, water, light, or nutrients (Duchene et al. 2017). In particular, intercropping with legumes – which can fix atmospheric nitrogen – can reduce the need for synthetic fertilizers (Jensen et al. 2020). In addition, intercropping helps reduce pest and disease pressure: by diversifying potential hosts and creating physical barriers, it slows the development and spread of fungal and bacterial diseases, therefore reducing the need for pesticides (Zhu and Morel 2019). Finally, intercropping plays an essential role in crop resilience to climatic variability, which is crucial in the context of climate change (López-Angulo et al. 2023).

However, the success of such a system depends on the choice of species and varieties, as some combinations of species or cultivars perform better than others (Stefan et al. 2025; Schöb et al. 2023). Indeed, one of the main challenges in intercropping is to find a balance between interspecific complementarity and competition; for instance, cereals, with their rapid growth and ability to capture light and nutrients efficiently, can easily dominate legumes such as peas and reduce their development (Paolo Annicchiarico et al. 2021). Such competitive interaction requires strategic variety selection for increased performance in mixtures (P. Annicchiarico et al. 2019). In addition, the spatial design – row spacing and alternation as well as density of each species – is of equal importance for optimal growth and yields (Cheriere et al. 2020; Stefan et al. 2022b). Finally, harvest management represents a significant logistical challenge in intercropping. The differential maturity of associated species complicates harvest synchronization, requiring adaptations in agricultural equipment and post-harvest strategies to minimize losses and preserve grain quality (Paolo Annicchiarico et al. 2021). These challenges highlight the importance of an integrated approach, combining species and varietal selection, optimization of cultural practices, and technological innovations to maximize the benefits of intercropping while limiting its constraints.

Here we used an extensive field trial experiment to investigate the dependence of intercropping performance on both species and variety choices. To do so, we evaluated twelve different pea varieties when intercropped with two species, namely barley and lentil, and in pure stands. Pea–barley is a classic intercropping combination, in which barley provides physical support to the pea but is also rather competitive (Corre-Hellou et al. 2011; Hauggaard-Nielsen et al. 2001). On the contrary, pea–lentil has rarely been explored, as legume-legume intercrops are not common (Vonzun et al. 2023). Lentil has a lower competitive ability than cereals, which is why we chose this crop to see whether pea would perform better when associated with it. Furthermore, lentil has a high market potential for human consumption and therefore represents an increased income opportunity. We therefore assessed the agronomic performance and grain yield of various pea varieties grown as pure stands, intercropped with barley, and intercropped with lentil during two growing seasons in Switzerland. In addition to yield, we also measured lodging and disease severity. The objectives of the study were to (1) evaluate the performance of pea intercropped with barley and lentil and (2) identify pea varieties particularly adapted to growing in crop associations.

2 | Materials and Methods

2.1 | Experimental Sites

The field experiment took place in 2022 and 2023 in Changins (Nyon), Switzerland (46° 24.04' N, 6° 15.49' E) on silty soils. Climatic conditions and field properties for the two growing seasons are described in Figure S1 and Table S1. The main differences between year 2022 and 2023 were reflected in precipitation: in 2022, precipitation was high in February and rather low in March, May and July, whereas 2023 was a much wetter year, with an important amount of precipitation in March, April and June. Average temperatures indicated that 2022 was overall warmer than 2023, particularly during the months of May and July.

2.2 | Experimental Design

The experimental design was a split-plot with the cropping system as a main plot (pure stand, associated with barley, or associated with lentil) and pea genotypes as subplots, with 3 replicates per genotype × association (Figure S2). Peas and the associated crops were sown on the same days, on 08.03.2022 and 21.02.2023, at a density of 90 seeds/m^2 for peas (in pure stand), 300 seeds/m^2 for barley, and 370 seeds/m^2 for lentils. In intercropped plots, the relative density was 80%/30% of the density in pure stand for peas and the associated crop, respectively. Microplot size was 12 m^2 (2 m × 6 m). 3 replicates of barley and lentil in pure stand were sown at the end of each row in order to calculate the Land Equivalent Ratio (LER) for each

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association (see Figure S2). Guard rows of pea (variety Astronaute) were established around the experimental field to reduce edge effects. Harvest dates were 29.06.2022 and 28.06.2023. Detailed technical itineraries for the field trials are available in Table S1.

2.3 | Plant Material

The study was conducted using a set of 12 pea genotypes: Astronaute (RAGT 2n, France), Torpedo (P.H. Petersen Saatzucht Lundsgaard GmbH, Germany), Avatar (Selgen, Czech Republic), Paprika (Laboulet Semences, France), Kameleon (KWS Momont, France), Sallam (GZPK, Switzerland), Belcon (GZPK, Switzerland), Conpro (GZPK, Switzerland), Greenway (Nordic Seed, Denmark), Orchestra (RAGT 2n, France), and Kazek (Danko Saatzucht Deutschland GmbH, Germany). One genotype of barley (Atrika, KWS, Germany) and one lentil (Anicia, AgriObtention, France) were used as associated crops.

2.4 | Data Collection

To assess the agronomic performance and yield potential of the studied varieties, several parameters were measured throughout the growth cycle under field conditions.

2.4.1 | Lodging

Lodging severity of the different pea varieties was assessed by visual observations once per season. The observation was made in June. A rating based on a scale of 9 scores was used to quantify the intensity of the lodging in the plot. A score of 1 corresponded to the total absence of lodging, with all the stems remaining straight. A score of 3 indicated an inclination of about 30 degrees of all the stems or localised lodging on about a quarter of the surface. A score of 5 indicated a 45-degree incline of all the stems or pronounced lodging over half the surface area. A score of 7 corresponded to an incline of approximately 60 degrees or lodging affecting ¾ of the surface area. Finally, a score of 9 indicated total lodging of the plot.

2.4.2 | Diseases

The rating of ascochyta was carried out at the grain filling stage by making observations in two distinct locations per microplot. These observation points were selected at random, one per half-plot, being careful to avoid lines at the edge of the plot. For each location, two parameters were evaluated: the percentage of necrotic canopy surface, estimating the proportion of the plant showing symptoms, and the percentage of necrotic plant tissue, reflecting the extent of lesions on the leaves. The rating was carried out visually by gently opening the vegetation to observe the base of the plants. Ascochyta infestation only occurred in 2023.

The evaluation of oidium on peas was carried out after flowering in order to score the intensity of the disease at a time when the symptoms were sufficiently expressed and varietal differences distinguishable. A rating based on a scale of 9 scores was used: A score of 1 for no symptoms, an infestation rating of 2 for very low symptoms (a few oidium stains in the plot), 3 for low infestation (most plants present a few stains but less than 5% of leaf area with symptoms), 4 for low to medium infestation (approximately 5% of total leaf area diseased), 5 for medium infestation (15% of total leaf area showing symptoms), 6 for medium to high infestation (25% of total leaf surface with symptoms), 7 for high infestation (50% of total leaf surface with symptoms), 8 for high to very high infestation (75% of total leaf area with symptoms), and 9 for very high infestation (all leaves entirely covered with symptoms). If, after the first rating, the disease continued to progress and led to changes in the susceptibility of the varieties, an additional rating was carried out.

2.4.3 | Grain Yield and Yield Components

At maturity, each plot was harvested using a combine harvester (Zürn 150, Schontal-Westernhausen, Germany), providing the total grain weight of the plot. In intercropped plots, the two species were harvested together. A sample of 1 kg was taken from the harvested material of each plot and sieved to separate peas from the associated crop and impurities with a sieving-blowing machine LA-LS-P (Westrup A/S, Slagelse, Denmark). Peas, barley and lentils were then separated, weighed, analysed for their water content with a Dickey–John machine (GAC 2100, Auburn, IL, USA), then oven-dried for 48 h at 60°C. Yield data were standardized at the conventional humidity content, i.e., 13.5% for peas, 14.5% for barley, and 12.0% for lentils.

2.5 | Data Analyses

2.5.1 | LER

The Land Equivalent Ratio (LER) was calculated to evaluate the efficiency of land use in intercropping systems compared to monocultures. This metric expresses the relative amount of land required in monoculture to produce the same yields as those obtained in intercropping.

The LER is calculated using the following formula:

$$LER = (Yinter1/Ymono1) + (Yinter2/Ymono2)$$
$$= pLER_1 + pLER_2$$

Yinter i: yield of species i in intercrop

Ymono i: yield of species i in monoculture

$pLER_i$: partial Land Equivalent Ratio of species i

LER greater than 1 indicates that intercropping is more efficient in land use than monoculture, producing equivalent or higher yields on a smaller area. A LER equal to 1 signifies that intercropping and monocultures have similar efficiency, while a LER less than 1 indicates lower efficiency of intercropping.

2.5.2 | Statistical Analysis

In a first step, we analysed the general effect of intercropping on pea performance across all pea varieties. This was done using linear mixed-effects models, with cropping treatment (monoculture vs. mixtures), year, and their interaction as fixed

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factors. Random effects included replicates within horizontal blocks, as well as pea variety. The model structure was:

$$response \sim cropping\ treatment * year + (1|block/rep) + (1|pea\ variety) \quad (1)$$

We then assessed the effect of the associated crop by replacing intercropping treatment with associated crop (barley vs. lentil), resulting in the following model:

$$response \sim associated\ crop * year + (1|block/rep) + (1|pea\ variety) \quad (2)$$

Models (1) and (2) were used to analyse total yield, pea yield, LER and partial LER. To analyse lodging score and ascochyta severity, we used generalized linear mixed-effect models with a Poisson family, with the same fixed and random effects as described above. Post-hoc pairwise comparisons were computed using Tukey test from the *emmeans* function (Lenth 2021). Statistical significance was assessed at $\alpha = 0.05$.

In a second step, we investigated the effects of the different pea varieties on pea performance in intercropping. For this, we used linear mixed-effects models with year, associated crop (barley vs. lentil), pea variety, and their interactions as fixed factors. Random effects included replicates within horizontal block:

$$pea\ performance \sim associated\ crop * pea\ variety * year + (1|block/rep) \quad (3)$$

To check for links between partial LER and pure stand yield, we used linear regressions. For all models, statistical significance was assessed at $\alpha = 0.05$. Homogeneity of variance and normality of residues for linear mixed models were assessed visually. All the statistical analyses were carried out using R software version 4.4.2 (R Core Team 2019).

3 | Results

3.1 | Yield

3.1.1 | Total Yield

When looking at the effects of cropping treatment independently of pea variety, total yield was significantly affected by monoculture versus mixtures, year, and the interaction between the two (Figure 1a, Table S2). More precisely, total yield was significantly lower in 2023 compared to 2022 (43.1 vs. 29 dt/ha, i.e., a reduction of 33%). The effect of cropping treatment differed across years: in 2022, monocultures exhibited a significantly higher yield than intercrops (+ 15%), while in 2023, we observed the reverse pattern, with monocultures having a lower yield than intercrops (–13%). Similarly, there was a significant effect of associated crop (lentil vs. barley), year, and their interaction on total yield (Figure 1b, Table S3). In detail, in 2022 there was no significant difference between the total yield of both intercrops, whereas in 2023, the intercrop with barley yielded significantly more than the intercrop with lentil and pea pure stands (Figure 1b, +25%).

When incorporating the effect of pea varieties, results showed a significant effect of pea variety on total yield ($p = 0.03$, Table S4). This effect was not involved in interaction with associated crop ($p = 0.17$), with year ($p = 0.27$) or with year × associated crop ($p = 0.06$), indicating that the effect of variety is stable across years and associated crop. Pairwise comparisons (Table S5) further indicated that the variety Torpedo yielded less than most others, and that variety Greenway performed better than most others. Furthermore, variety Kagnotte was also better than Paprika and Sallam.

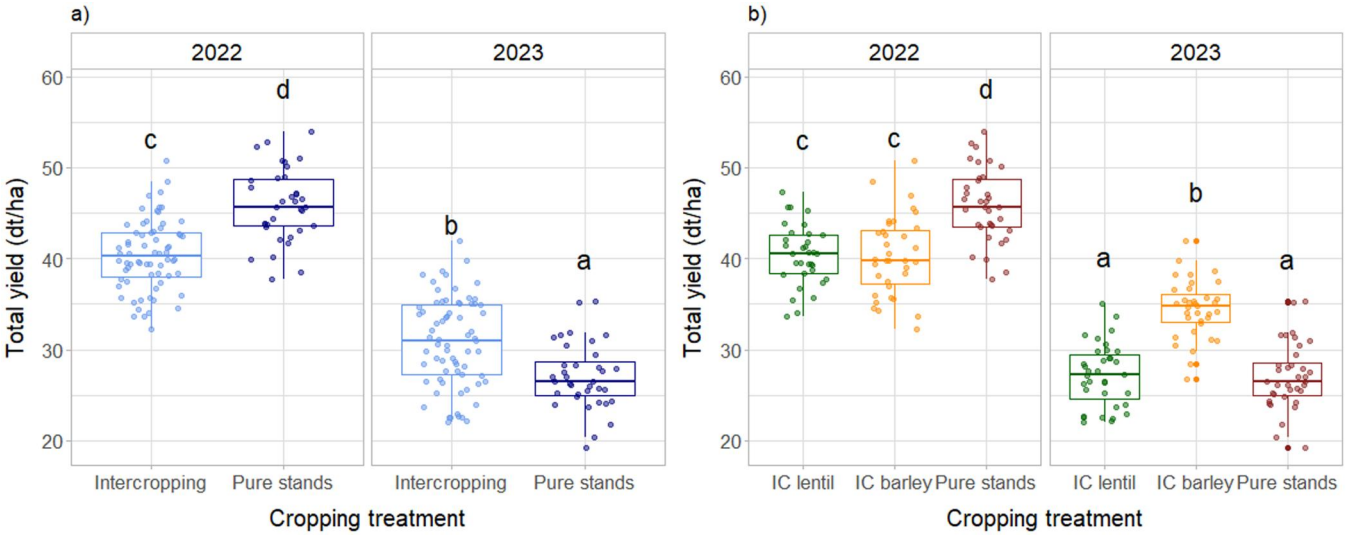


FIGURE 1 | Total yield (dt/ha) for both years by trial type: (a) in intercropping versus pure stands and (b) in intercropping (IC) with lentil, intercropping with barley, and pure stands. Horizontal lines within the box represent the median of the data, boxes extend from the lower to the upper quartiles (25% and 75%), with vertical lines extending from the hinge of the box to the smallest and largest values, but no further than 1.5 x the interquartile range. Datapoints are plotted. Different letters above the boxes represent significant differences between treatment (*p*-value threshold of 0.05).

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3.1.2 | *Pea Yield*

like total yield, pea yield was also significantly higher in 2022 than 2023 (+ 66%, Table S6). In addition, monocultures yielded more than intercrops in 2022 (+ 44%, Figure 2a). When looking at differences between associated crops, the same trend was noticed in both years, with pea yield significantly lower when intercropped with barley compared to monoculture (−47% in 2022, −52% in 2023, Table S7, Figure 2b) and intercrop with lentil (−34% in 2022, −48% in 2023, Table S7, Figure 2b). This indicates that pea was generally suffering when intercropped with barley, while barley was thriving in these conditions.

Diving deeper into the detailed impacts of pea varieties, we found significant effects of pea variety (Table S8, $p < 0.001$), but also pea variety × associated crop ($p = 0.027$) and pea variety × year ($p = 0.008$). Pairwise comparisons showed that most varieties have a higher pea yield when mixed with lentils than when mixed with barley, and a lower pea yield when mixed with barley than grown in pure stands. Furthermore, when grown with lentils, varieties Astronaute, Greenway and Kagnotte had a significantly higher yield than Paprika, Sallam or Torpedo. Greenway and Kazek stood out positively when grown with barley, in contrast to Torpedo, Paprika and Sallam (Figure S3).

3.2 | LER

Land Equivalent Ratio was significantly affected by year and associated crop × year (Table S9). It was notably higher in 2023 compared to 2022 (average in 2023: 1.024; in 2022: 0.92), with an increase of 11%. In 2023, LER was significantly higher when intercropped with lentil (average of 1.16) compared to barley (average of 0.89, +30%, Figure 3). Importantly, in 2023, the pea–lentil intercrop had an average LER higher than 1, indicating a higher land use efficiency of the intercrop.

We then further looked at the effect of pea variety by analysing partial LERs (pLER) for each pea variety × association × year. Results indicated that pLERs were significantly affected by associated crop, pea variety, year, as well as associated crop × year (Table S10). Post hoc Tukey comparisons further showed significant differences between Belcon (0.81) and Orchestra (0.59), Belcon and Paprika (0.62), Belcon and Sallam (0.62), Greenway (0.76) and Orchestra, Kazek (0.76) and Orchestra, Kazek and Paprika (see Table S11, Figure S4). Belcon, Greenway and Kazek therefore appeared as particularly suited for growing in intercrops, while Orchestra, Paprika, and Sallam were not.

Surprisingly, there was no effect of variety × associated crop, nor of variety × associated crop × year, indicating that none of the varieties was performing relatively better or worse in terms of LER with lentil compared to barley.

Partial Land Equivalent Ratios were significantly negatively correlated with pea yield in pure stands (Figure 4) in 2023 with both lentil and barley, and in 2022 when associated with lentil. This suggests that varieties tend to perform better in intercropping when they have a lower yield in pure stand. This was notably the case for Kazek and Belcon. Greenway on the contrary had a high pLER in association but also a high yield in pure stand. At the other end of the spectrum was Orchestra, with a high yield as a pure stand but the lowest pLER when associated.

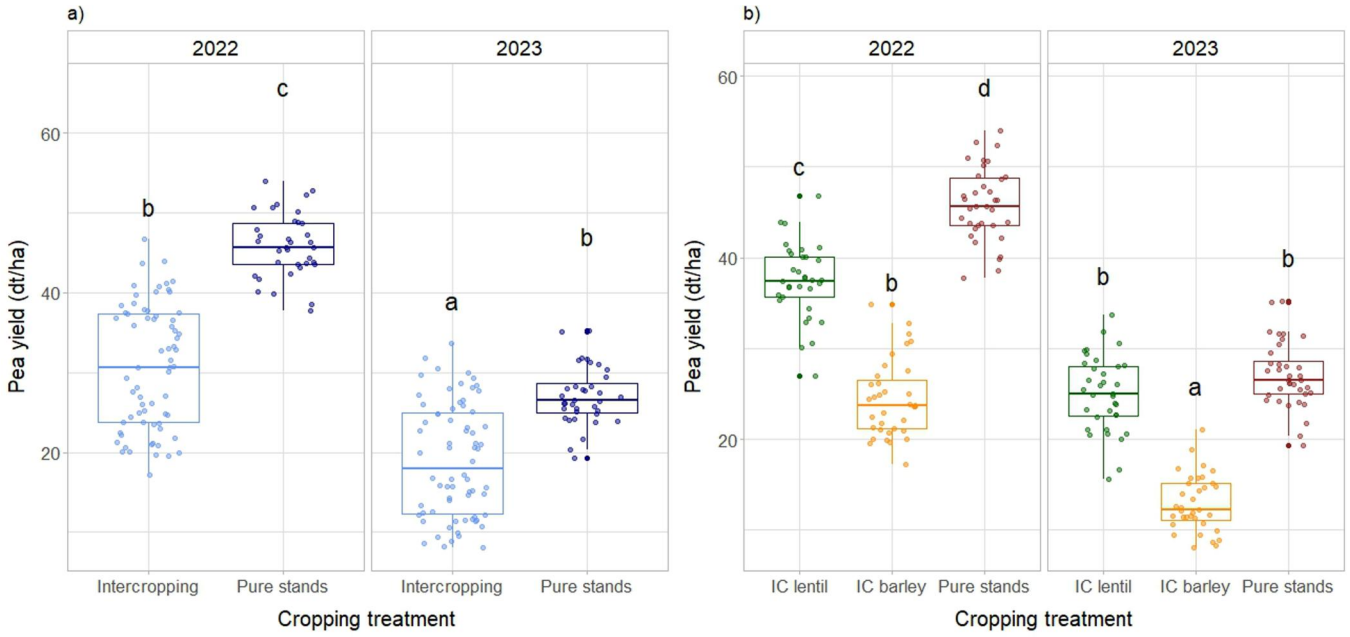


FIGURE 2 | Pea yield (dt/ha) for both years by trial type: (a) in intercropping versus pure stands and (b) in intercropping (IC) with lentil, intercropping with barley, and pure stands. Horizontal lines within boxes represent the median of the data, boxes extend from the lower to the upper quartiles (25% and 75%), with vertical lines extending from the hinge of the box to the smallest and largest values, but no further than 1.5 x the interquartile range. Datapoints are plotted. Different letters above the boxes represent significant differences between treatment (*p*-value threshold of 0.05).

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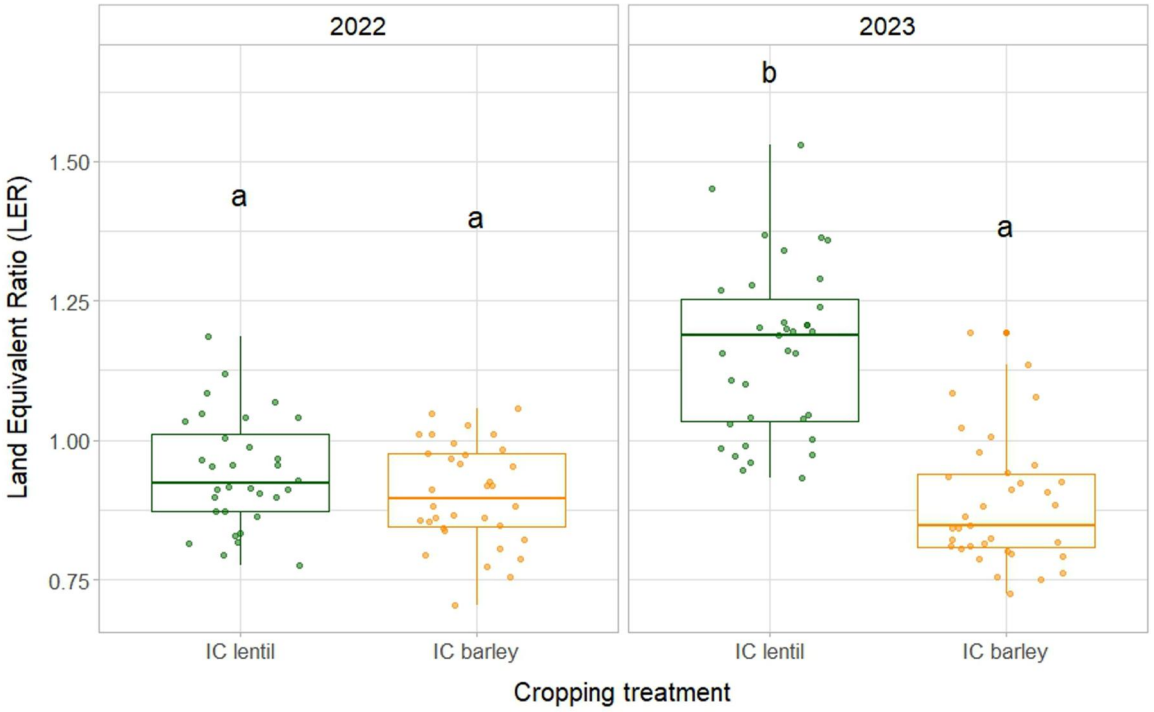


FIGURE 3 | Comparison of LER for Intercropping (IC) with lentil and interropping with barley in 2022 and 2023. LER > 1 indicates a positive association, while LER < 1 indicates negative association. Horizontal lines within the box represent the median of the data, boxes extend from the lower to the upper quartiles (25% and 75%), with vertical lines extending from the hinge of the box to the smallest and largest values, but no further than 1.5 x the interquartile range. Datapoints are plotted. Different letters above the boxes represent significant differences between treatment (*p*-value threshold of 0.05).

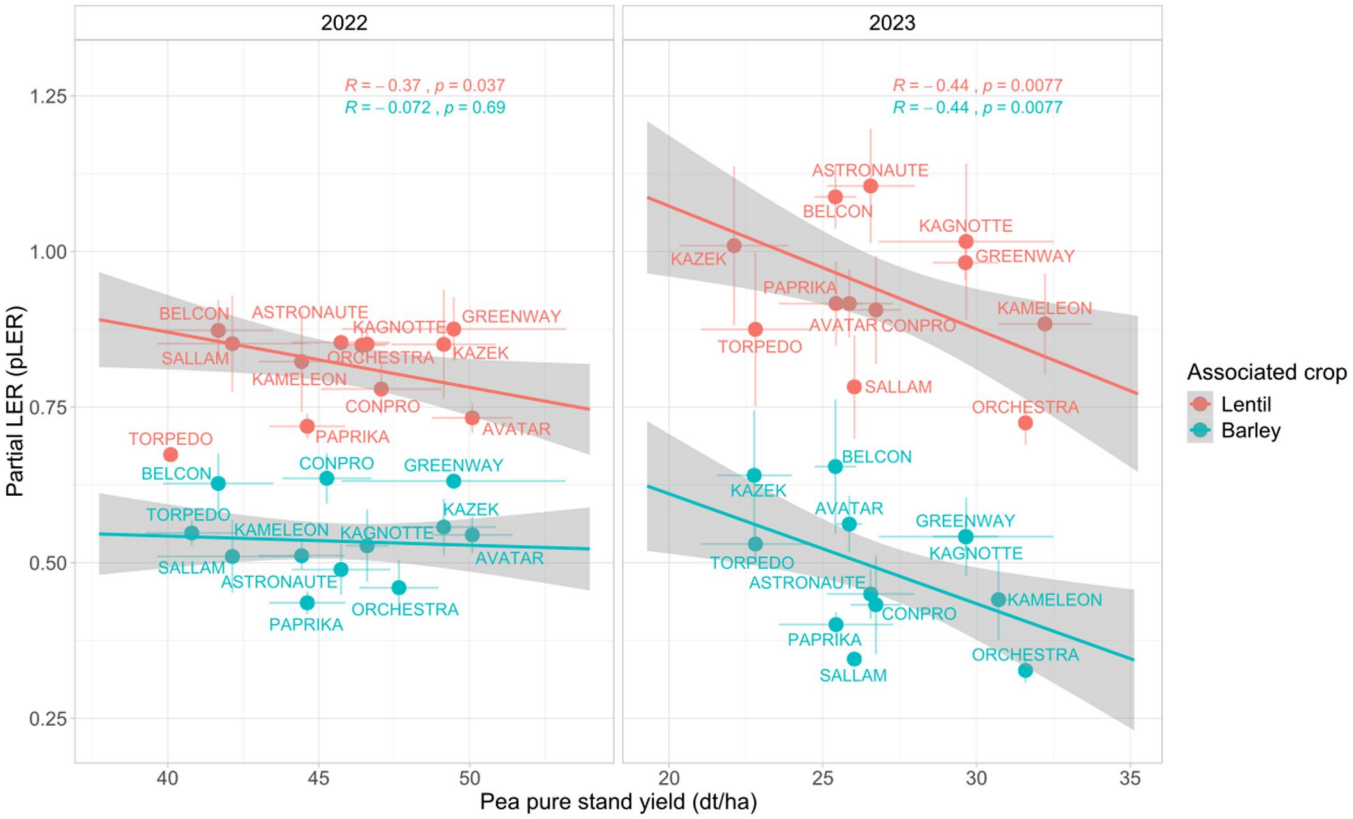


FIGURE 4 | Relationships between partial Land Equivalent Ratio of pea (pLER) and pea yield in pure stand (dt/ha), in year 2022 and 2023, when intercropped with lentil (red) and barley (blue). Regression lines, regression coefficients and p-value associated with these regressions are shown.

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3.3 | Lodging

When looking only at the effect of cropping treatment, we observed a significant effect of year and associated crop, with barley intercropping reducing lodging compared to intercropping with lentil (−70%) and compared to pea monocultures (−73%) (Table S12). Pea–barley intercrop clearly stands out by limiting the lodging phenomenon, as confirmed by the boxplots in Figure S5a. When incorporating pea variety as an explanatory factor, we did not observe any effect of variety nor any of its interactions on lodging severity (Table S13).

3.4 | Ascochytosis

The analysis of variance highlighted a significant influence of associated crop ($p < 0.001$), pea variety ($p < 0.001$), as well as their interaction ($p < 0.001$) on total necrotic area by ascochyta blight (Table S14). Post hoc comparisons revealed that peas intercropped with barley significantly reduced the development of ascochyta on peas compared to pure peas ($p = 0.0002$) or to pea–lentils ($p = 0.003$).

Furthermore, analysis of the graph comparing ascochytal development with the different varieties and associated crops (Figure 5) and pairwise post hoc analyses of the model indicated that Orchestra, Kameleon, and Greenway particularly benefited from being intercropped with barley, while Kazek and Paprika did not benefit from either association.

4 | Discussion

Our study investigated the performance of twelve different pea genotypes when intercropped with two species, namely barley and lentil. Over the course of two growing seasons, yield, disease incidence, and other agronomic parameters were evaluated. Our study showed that intercropping pea with lentil was particularly beneficial for pea yield, notably during relatively low productive years. We further identified pea genotypes particularly well suited for growing in crop associations. Overall, pea intercropping represents a promising way to increase the resilience of this sensitive crop.

4.1 | Intercropping Pea With Lentil Allowed to Maintain Pea Yield

Our study showed that lentil was a surprisingly good companion for association with pea. This was rather unexpected, as legume-legume intercropping systems are rare in literature and in practice, compared to cereal-legume (Bedoussac et al. 2015). Land Equivalent Ratio showed an improved land use efficiency compared to pea monoculture only in the case of pea–lentil intercropping, indicating a benefit of this association for yield. With barley, Land Equivalent Ratio and pea yield were drastically reduced, suggesting that the association was not successful. This is perhaps unsurprising, as cereals have been shown to be too competitive for legumes if the sowing ratios and densities are not adapted to the lower competitive ability of the pea

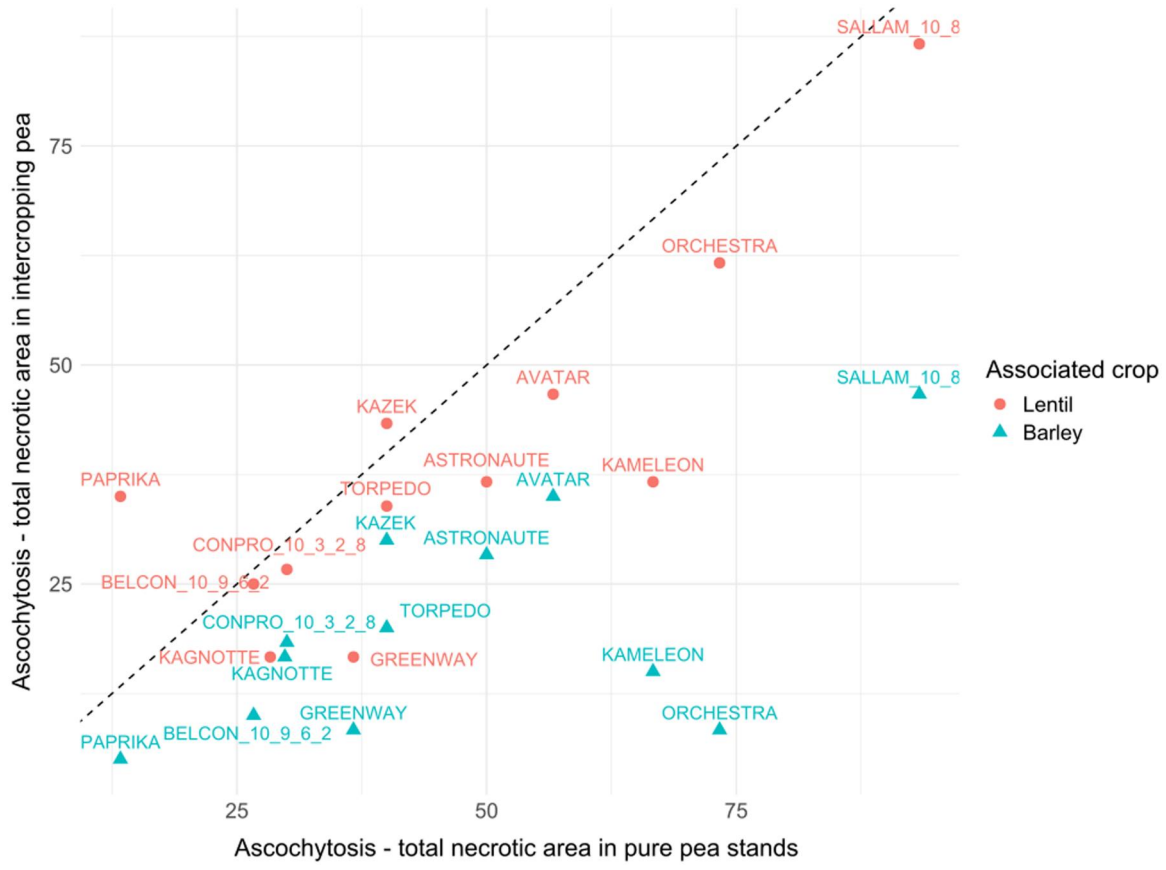


FIGURE 5 | Relationship between Ascochyta total necrotic area in pure pea stands and in association with lentil (red) and barley (blue). The dashed line represents the 1:1 line.

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(Mahmoud et al. 2022). Cereals are strong competitors, notably due to their high growth rate at early life stages, their extensive root systems, and high uptake of nitrogen (Bertholdsson 2005; Stefan et al. 2021). Such competition could be better managed or avoided with an increase in the pea density (e.g., to 100%) or a reduction in barley density, for instance to 20% instead of the 30% used in the present study. Land Equivalent Ratio with barley always remained below 1, despite improving pea lodging and reducing pea disease. Such beneficial side effects are consistent with the literature, as barley – and in general, cereals – are known to provide physical support to the legume growing beside it (Bedoussac et al. 2015). This physical support helps limit pea lodging, facilitates harvesting, and reduces post-harvest losses caused by high moisture (Podgórska-Lesiak and Sobkowicz 2013). Furthermore, barley acted as a barrier for disease spread (Kinane and Lyngkjaer 2002). This can either be due to a decrease in humidity – as a consequence of the reduction of lodging, and hence an improvement of the micro-climate in the canopy which commonly limits disease spread (Corre-Hellou et al. 2011; Schoeny et al. 2010) – or simply because barley physically limits pathogen dispersal (Schoeny et al. 2010). Yet, this improvement in lodging and disease development in pea did not allow to compensate for the higher competitive ability of barley.

In contrast, the association with lentil was beneficial (with LER > 1) even though there was no improvement in pea lodging and a rather small reduction in pea disease severity. Importantly, lodging was not significantly aggravated in this association compared to the pure stand, indicating that lentil does not compromise the canopy structure of the pea, probably due to its small morphology and, hence, weak physical influence. The success of pea–lentil intercropping could be due to the lower competitive ability of the lentil (Tepe et al. 2005) – which may give enough space and light for the pea to properly grow, its ability to fix nitrogen (Abi-Ghanem et al. 2011), or other potential mechanisms, such as complementarity in root distribution (Ravenek et al. 2014) or phenology (Engbersen et al. 2021). The beneficial effect of lentil on pea growth was particularly marked in the year 2023, which was less productive than 2022 due to higher precipitation during the phases of growth and maturity (Figure S1).

All these results show that crop associations can act as an important lever to optimise pea yield and to maintain pea productivity, especially during climatically unfavourable years. These are well-known positive effects of crop diversity in agriculture, which notably include increasing yield stability when climatic conditions are variable (López-Angulo et al. 2023), and increasing yields in low-productive systems (Franco et al. 2015). However, little is known of the effects of different genotypes on intercropping benefits, as most studies are usually performed with one genotype of each species. That is why, here, we tested twelve different pea varieties, in order to assess whether some are more adapted to intercropping than others.

4.2 | Comparison of Tested Pea Varieties

Although most agronomic studies on intercropping have used a single genotype besides the associated crop, research has highlighted significant differences between crop varieties when they are intercropped (Magnin et al. 2026; Muñoz-Escribano et al. 2025). Indeed, pea genotypes do not all react similarly to the presence of an associated crop (Hauggaard-Nielsen and Jensen 2001). Some genotypes may, for instance, better tolerate competition than others, which allows them to maintain a reasonable yield level when intercropped (Lebreton et al. 2024). The study by Barillot et al. (2014) notably highlighted that certain pea varieties are better suited to intercropping with wheat, due to morphogenetic and architectural trait differences that influence their ability to withstand light competition. Furthermore, the traits required for high performance in intercropping may not be the same as those required for high yields in pure stands (Stefan et al. 2022a; Lebreton et al. 2024). Decades of breeding for monocultures have indeed targeted performance at the group level (i.e., group selection) rather than at the individual level, which has favoured varieties with lower competitive abilities that performed well at very high densities (Denison 2012). This could have led to the emergence of varieties with relatively low soil cover ability, low morphological plasticity, and high uniformity. In contrast, varieties that are performing well in intercropping may be more competitive and less uniform, grow wider, and have more trait plasticity for increased adaptability to neighbouring diversity (Ajal et al. 2022; Abakumova et al. 2016). Varietal selection is, therefore, a strategic lever for optimizing yields in intercropping.

In the present study, five pea varieties stood out in particular for their good adaptation to intercropping with barley and lentils. First, variety Greenway proved to be competitive in terms of yield in both 2022 and 2023. This variety was successful both as a pure stand and when intercropped: its high LER (Land Equivalent Ratio) confirms its ability to maximize productivity when associated, regardless of the two constrating annual conditions. Our study also identified the varieties Astronaute, Kagnotte, Kazek and Belcon as potential good partners for intercropping. Kazek and Belcon had a rather low or average performance when grown in pure stands, which can explain why their partial Land Equivalent Ratios were high. This shows that several indicators are needed to fully grasp the behaviour of intercropped species: relative indices, like LER, are useful to assess the system as a whole, but when looking at individual components, absolute yields remain informative and necessary.

Varieties Orchestra, Paprika and Sallam turned out to be the least successful in intercropping, with much lower yields and LERs; among these, Orchestra and Sallam were really sensitive to Ascochyta. These results strongly limit their potential for use in intercropping: Orchestra notably was one of the highest-yielding varieties when grown in pure stands, but one of the lowest-yielding in intercropping. These differences highlight the importance of rigorous varietal selection in order to maximize productivity and stability in intercropping systems.

4.3 | Caveats, Limitations, and Next Steps

While intercropping offers many agronomic benefits, particularly in terms of yield stability, disease reduction, and lodging limitation, it also introduces a form of competition between species (Hauggaard-Nielsen et al. 2006). Optimizing these combinations depends on several criteria: precise adjustment of seed densities to prevent one species from dominating the other (Neugschwandtner and Kaul 2014), the choice of varieties with

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compatible architecture that promotes complementarity (Hauggaard-Nielsen and Jensen 2001), and an optimized sowing schedule that allows for more efficient distribution of resources (Huang et al. 2018). Considering the results of our study, it might therefore be wise to reduce the sowing density of the associated crop relative to the sowing density of peas in order to reduce the competitive effect, particularly for the barley combination. An integrated approach combining varietal selection and technical adjustments would mitigate the negative effects of competition and maximize the benefits of intercropping. Investigating specific pea traits linked to complementarity in intercropping systems would also bring additional information and further help guide cultivar selection.

Furthermore, the economic aspect of these crop associations must be taken into greater consideration. While they improve crop resilience, they can also generate additional costs related to harvest management, post-harvest sorting, and the availability of commercial outlets (Manevska-Tasevska et al. 2024). Thus, the success of these systems also depends on finding a balance between agronomic benefits and economic viability. The whole value chain of niche products must be considered and established if not yet available (Schulp et al. 2024) in order to increase their market potential.

Finally, the contrasting responses observed between the 2 years highlight the importance of environmental conditions in determining the performance of intercropping systems. Such variability and context-dependence have been widely shown in the literature (Bousselin et al. 2024; Brooker et al. 2024). In 2022 – which was a highly productive year – pure stands showed higher yields, whereas in 2023 – a less productive year – intercropping increased overall yield by 13%. The 2 years differed substantially in water conditions during the early stages of crop development. In 2023, precipitation was considerably higher in March, shortly after sowing, resulting in wetter-than-optimal conditions during crop establishment. These conditions may have negatively affected early plant development, which could have contributed to the lower overall yields observed in 2023. Previous research has suggested that the benefits of intercropping are more likely to emerge under suboptimal growing conditions, when environmental stress limits the performance of individual crops (Bertness and Callaway 1994; Brooker et al. 2008). Under such conditions, complementarity between species may become more advantageous, not only through more efficient resource use (Mahmoud et al. 2022) and increased facilitation (Brooker et al. 2021), but also through differences in their tolerance and response to environmental stressors (Su et al. 2025; Stefan et al. 2024).

The earlier sowing in 2023 may also have contributed to differences in crop development and performance between years. However, sowing dates were inherently determined by field and weather conditions and therefore cannot be separated from the climatic conditions of each year. Consequently, we cannot attribute the differences observed between years to a specific environmental or management factor. Given that our study was conducted over only 2 years and at a single site, the results shouldbe interpreted with caution. Further multi-year and multi-site trials are needed to determine under which environmental conditions particular crop associations and pea varieties are most likely to benefit from intercropping. In Switzerland, trials across several locations and growing seasons would provide a stronger basis for assessing the consistency of the associations identified in the present study.

5 | Conclusion

Under certain conditions, intercropping offered significant advantages in terms of productivity, disease management, yield stability, and land use efficiency, as demonstrated by the pea–barley and pea-lentil combinations studied here. Barley played a key role in limiting lodging and reducing the development of ascochyta blight, while lentils allowed to achieve better pea productivity under the unfavourable conditions of 2023. Thus, under such conditions the pea–lentil intercropping model is advantageous. Yet, these combinations were not without constraints, particularly in terms of variability in performance depending on climatic conditions. This is why additional trials should be performed to explore this intercropping system, especially because our study was limited to only 2 years of data at a single location.

Interestingly, to some extent, the characteristics of the two associated crops are complementary. In a mixture with both, barley could continue giving stability while lentil would deliver nitrogen. In this sense, an interesting future approach might be the partial substitution of barley with lentil, which would also allow for a reduction in barley density and thereby limit excessive competition. This triple intercrop may balance itself, achieving higher performance than the present two crop associations.

In any case, the choice of associated crop and pea varieties appear to be a major strategic lever for maximizing the benefits of intercropping. Certain pea varieties, such as Greenway, have proven to be particularly well suited for these systems, while others have limitations. Optimizing these intercropping combinations therefore requires an integrated approach, combining varietal selection, adjustments to sowing densities and other parameters of the associated crop, as well as an adapted value chain for market opportunities.

Author Contributions

Laura Stefan: formal analysis, visualisation, writing – original draft, writing – review and editing. **Klervie Bourgoin:** data curation, visualisation, writing – original draft, writing – review and editing. **Eve-Anne Laurent:** investigation, resources, data curation, writing – review and editing. **Adrien Mougel:** investigation, writing – review and editing. **David Schneider:** investigation, data curation, writing – review and editing. **Alice Baux:** conceptualization, funding acquisition, resources, supervision, writing – review and editing.

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Conflicts of Interest

The authors declare no conflicts of interest.

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Data Availability Statement

Data is available at https://doi.org/10.5281/zenodo.23368412.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.

Supporting File: sae270228-sup-0001-Supp_pea_genotypes_intercropping_R1.docx.

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