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Mixed Cropping of Narrow-Leaved Lupin With Oat Improves Grain-Yield Stability Across Five European Locations

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ABSTRACT

Pulse × cereal mixtures are promoted to stabilise yield and reduce fertiliser dependence, yet robust multienvironment evidence for narrow-leaved lupin (NLL, *Lupinus angustifolius*) × oat (*Avena sativa*) mixed cropping remains scarce. We tested whether NLL × oat mixtures maintain productivity while enhancing grain-yield stability. A randomised complete block design (four blocks) evaluated three NLL and three oat varieties grown in pure stands and as all nine pairwise mixtures with a replacement design (NLL 90%, oat 10% of pure-stand density). The experiments ran for 13 environment-years across five European locations. Productivity was summarised with land equivalent ratio (LER) and crop performance ratio (CPR). Yield stability was assessed using (i) the coefficient of variation (CV), (ii) Finlay–Wilkinson regression slope b_1 and Eberhart–Russell deviation variance (S^2_{di}), and (iii) additive main effects and multiplicative interaction-derived weighted average of absolute scores (AMMI-WAAS). Mixed-effects models were used to assess mixed cropping effects. Across environments, LER did not differ from unity ($LER = 1$) whether fertilised or unfertilised oat monocultures were the reference. By contrast, total CPR and oat-specific CPR consistently exceeded 1 (mean CPR = 5.3; CPR_N = 4.6), indicating system-level gains driven by the oat component without penalising NLL. While CVs did not separate treatments, many mixtures and pure stands were environmentally responsive, but the most stable mixtures combined near-average responsiveness with very low variation and sensitivity to the environmental conditions (Bison × Probor and Troll × Jowisz). Lastly, fertilised oat monocultures were more stable than unfertilised counterparts. Stability gains arose from reduced environmental sensitivity of the mixture rather than the individual variety, underscoring the need to evaluate mixtures directly rather than inferring stability from monocultures. Our results support deploying pulse-centric cereal × legume mixtures as a pragmatic option to buffer climate variability while sustaining protein-rich production.

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1 | Introduction

Global demand for protein-rich plants is growing while climate volatility continues to undermine the year-to-year reliability of monocultures (Ismail et al. 2020; Raseduzzaman and Jensen 2017). Mixed cropping of cereals with grain legumes (pulses) has re-emerged as a promising strategy to improve yield stability, decrease fertiliser dependence and improve resource-use efficiency (Kumawat et al. 2022; Raseduzzaman and Jensen 2017; Tang et al. 2021). Narrow-leaved lupin (NLL, *L. angustifolius* L.) is among the few pulses that combine high seed protein with the ability to thrive on nutrient poor soils (Lopez-Bellido and Fuente 1986); however, its sole-crop yield is notoriously unstable (Reckling et al. 2018). Oat (*A. sativa* L.) offers complementary morphology, rapid early growth and serves as a cereal break crop (e.g., Danso et al. 1993; Palmason et al. 1992). Integrating the two species in mixed cropping can therefore address both agronomic resilience and nutritional targets at farm and food-system level, respectively.

Numerous studies on genotype $\times$ cropping-system interactions have demonstrated that performance gains from cereal $\times$ pulse mixtures depend on both the mixed varieties and the environment in which they were evaluated (e.g., Demie et al. 2022). Meta-analyses consistently report average land-equivalent ratios (LER) between 1.2 and 1.3 for cereal-pulse mixtures, indicating a median 24% land-use advantage over pure stands (Demie et al. 2022). Grain-yield stability has been assessed with both static and dynamic metrics; in many cases, mixtures outperformed monocultures, yet the magnitude and drivers of this stability remain unclear (Raseduzzaman and Jensen 2017; Weih et al. 2021).

Fertiliser regimes of cereals in pure stands are pivotal for interpreting mixed-cropping metrics because both LER and crop performance ratio (CPR) are normalised by monoculture benchmarks (Hauggaard-Nielsen and Jensen 2001; Liu et al. 2023). The CPR compares observed mixed cropping output with the output expected from monoculture yields at the same sowing proportions (Zustovi et al. 2024). As a consequence of fertilising cereals in pure stands and the resulting increase in yield, the denominator of the cereal LER and CPR raises, which results in lower LER and CPR metrics for the same mixed crop. Though rarely investigated, reference treatment fertilisation exhibits significant effects on the mixed cropping performance metrics (Baxevanos et al. 2020). Additionally, medium to high fertiliser levels were shown to stabilise cereal yield (Silva et al. 2016). Thus, the choice of baseline (fertilised versus unfertilised) pure cereal stands directly affects mixed-cropping advantages in terms of productivity and stability metrics (Li et al. 2020; Mead and Willey 1980).

Despite this theory, robust multienvironment evidence for NLL $\times$ oat mixtures is scarce. Previous experiments have often been confined to single locations or ad-hoc varietal choices, leaving unresolved (i) whether crop-level indices such as the CPR validate classical LER assessments, (ii) how canopy height difference between the varieties influences the agronomic performance, (iii) whether the expected grain-yield stability gains of mixed cropping materialise across contrasting European agro-climates and (iv) how fertilisation of the pure reference cereal crop affects yield indices and stability metrics in mixed

stands. Addressing these gaps is critical, since pulses are pivotal to climate-change mitigation strategies and nitrogen-fertiliser reduction programmes (Rahman et al. 2022). Accordingly, we expect the following:

- Mixed stands to achieve LER values above 1, indicating superior land use compared with pure stands;
- Total CPR and the oat CPR to exceed unity (CPR above 1), reflecting an overall mixed cropping advantage;
- The CPR and LER to be relatively smaller if those metrics are compared with fertilised rather than unfertilised pure stands of oats;
- NLL $\times$ oat mixed cropping to increase both static and dynamic grain-yield stability across the five European locations relative to their corresponding pure stands; and
- The gain in grain-yield stability of mixed stands to be relatively smaller if that gain is compared with fertilised rather than unfertilised pure stands of oats.

2 | Methods

2.1 | Varieties

Three branching spring NLL and three spring oat varieties were chosen based on the breeders' fact sheets and the variety list of the German variety institute (Bundessortenamt 2021). Branching spring-NLLs and early maturing spring oat varieties were selected to increase the chances of coincidental ripening. The selected NLL varieties were as follows:

- Lunabor, bred by Saatzucht Steinach in Germany
- Probor, bred by Saatzucht Steinach in Germany
- Jowisz (synonym: Jupiter), bred by HR Smolic in Poland

The selected early maturing spring oat varieties were as follows:

- Bison, Hauptsaat für die Rheinprovinz GmbH, Germany, medium tall
- Lion, Nordsaat Saatzucht GmbH, Germany, medium tall
- Troll, Saatzucht Bauer GmbH & Co. KG, Germany, short

2.2 | Treatments and Experimental Design

The NLL and oat varieties were cultivated as spring crops in pure and mixed stands. The pure oat stands were fertilised according to the local guidelines (Table S1). In the mixed stands, each NLL variety was co-cultivated with each oat variety in a replacement design: the NLLs were sown at 90% of their pure stand's density, whereas the oats, due to their high competitiveness and the focus on the NLL crop, were sown at 10% of their pure stand's density (Böhm et al. 2008; Kato-Noguchi et al. 1994) (Table 1). The sowing amounts were adapted to the germination rate.

The fields of this 2-year study were arranged as a randomised complete block design (RCBD), consisting of four blocks. To

TABLE 1 | Treatments of the study: Narrow-leaved lupin and oat varieties, the stand (pure versus mixed), fertilisation, sowing ratios, respective sowing densities and corresponding amounts of seeds per hectare. For the two numbers present in the mixed treatments, the first one refers to narrow-leaved lupins, the second one to oats. The sowing density and fertilisation of the oat crop varied depending on the local recommendations.

Treatment	Stand	Fertilisation*	Sowing density** (plants m ⁻²)	Amount (kg ha ⁻¹)
Bison	Pure	No	300–400	168–224
Lion	Pure	No	300–400	121–161
Troll	Pure	No	300–400	110–147
Bison	Pure	Yes	300–400	168–224
Lion	Pure	Yes	300–400	121–161
Troll	Pure	Yes	300–400	110–147
Lunabor	Pure	No	120	220
Probor	Pure	No	120	170
Jowisz	Pure	No	120	214
Lunabor × Bison	Mixed	No	108/30–40	198/17–22
Lunabor × Lion	Mixed	No	108/30–40	198/12–16
Lunabor × Troll	Mixed	No	108/30–40	198/11–15
Probor × Bison	Mixed	No	108/30–40	153/17–22
Probor × Lion	Mixed	No	108/30–40	153/12–16
Probor × Troll	Mixed	No	108/30–40	153/11–15
Jowisz × Bison	Mixed	No	108/30–40	193/17–22
Jowisz × Lion	Mixed	No	108/30–40	193/12–16
Jowisz × Troll	Mixed	No	108/30–40	193/11–15

*Fertilisation was performed according to respective local guidelines (Table S1).
 **Novi Sad: 400 plants m⁻², Bad Vilbel and Gross Lüsewitz: 350 plants m⁻², Reckenholz and Seegräben: 300 plants m⁻².

lower the border effect to a minimum, each treatment was sown in three adjacent plots and only the middle plot was scored and harvested. The size of each harvested plot was 9 m².

2.3 | Locations, Husbandry and Weather Data

The experiments were conducted in Germany (Bad Vilbel and Gross Lüsewitz), Serbia (Novi Sad) and in Switzerland (Seegräben and Reckenholz) and were chosen based on their differing latitude, longitude, soil type (Table S1) and weather conditions (Table 2). In Switzerland, the experiments were performed in 2022 and 2023, while in Serbia and Germany, they were conducted in 2022, 2023 and 2024. All fields were ploughed and harrowed before sowing. The NLL seeds were inoculated with peat inoculum containing the rhizobium bacterium *Bradyrhizobium lupinus*. The inoculum was produced by Legume Technology Ltd., Nottinghamshire, UK. The same batch of inoculum was used in all years and stored dry and under exclusion of humidity at 10°C. After the inoculation, every 9 m² plot was sown individually in rows with 18-cm spacing. The plots were sown with a plot sowing tractor and real-time kinematic positioning-GPS-orientation. Spring-tine and shallow interrow cultivation was performed for the mechanical weeding. Chemical weed control was applied only at Gross Lüsewitz in 2022 and 2024 by using the pre-emergence herbicide Stomp Aqua; at all other locations, weeds were controlled mechanically or manually,

or no weed control was required (Table S1). The fertilised pure oats were fertilised during late tillering, before the elongation stage, according to local guidelines (Table S1). At Bad Vilbel, following organic production principles, horn grit was used as fertiliser.

2.4 | Harvest and Postharvest Analyses

Final plant canopy heights of the NLLs and oats were scored before harvesting. The crops were harvested with a plot combine harvester. The samples were then dried to a moisture content below 13%. In mixed treatments, the oats were separated from the NLLs with grain cleaners, where a 6-mm oval-cut sieve was deployed. The cleaned samples were weighed to measure the partial and total yield.

2.5 | Statistical Analysis

2.5.1 | Data Preparation and Calculations

Based on the primary data, productivity metrics were calculated to assess the LER of the mixture based on unfertilised oats (LER) and fertilised oats (LER_N) in pure stands, respectively. Furthermore, the CPR of each crop based on unfertilised oats in pure stands (CPRlupin and CPRoat), and based on fertilised oats

TABLE 2 | Weather data of the location and year in the cultivation seasons 2022, 2023 and 2024 (13 environment-years), retrieved from the closest official weather stations (the distance of the weather station to the location was between 0.25 and 5 km). Data were retrieved daily and the average temperature as well as the sum of precipitation across the location- and year-specific cultivation period were calculated.

Location and year	Mean temperature (°C)	Precipitation sum (mm)
Bad Vilbel 2022	13.4	174
Bad Vilbel 2023	13.1	293
Bad Vilbel 2024	13.8	402
Gross Lüsewitz 2022	11.8	234
Gross Lüsewitz 2023	11.8	258
Gross Lüsewitz 2024	13	367
Novi Sad 2022	22.7	75
Novi Sad 2023	17.8	234
Novi Sad 2024	17.4	175
Seegräben 2022	14.1	504
Seegräben 2023	13.8	500
Reckenholz 2022	17.7	244
Reckenholz 2023	17.4	362

in pure stands (CPR_{oat_N}) was determined, respectively, and the total CPR based on unfertilised oats in pure stands (CPR) and fertilised oats in pure stands (CPR_N) was calculated, respectively (Zustovi et al. 2024):

$$\text{LER} = \frac{\text{Yield}_{\text{lupin,mixed}}}{\text{Yield}_{\text{lupin,pure}}} + \frac{\text{Yield}_{\text{oat,mixed}}}{\text{Yield}_{\text{oat,unfertilised,pure}}}$$

$$\text{LER}_N = \frac{\text{Yield}_{\text{lupin,mixed}}}{\text{Yield}_{\text{lupin,pure}}} + \frac{\text{Yield}_{\text{oat,mixed}}}{\text{Yield}_{\text{oat,fertilised,pure}}}$$

$$\text{CPR}_{\text{crop}} = \frac{\text{Yield}_{\text{crop,mix}}}{p_{\text{crop}} \times \text{Yield}_{\text{crop,unfertilised,pure}}}$$

$$\text{CPR}_{\text{oat}_N} = \frac{\text{Yield}_{\text{oat,mix}}}{p_{\text{oat}} \cdot \text{Yield}_{\text{oat,fertilised,pure}}}$$

$$\text{CPR} = \text{CPR}_{\text{oat}} + \text{CPR}_{\text{lupin}}$$

$$\text{CPR}_N = \text{CPR}_{\text{oat}_N} + \text{CPR}_{\text{lupin}}$$

where

$\text{Yield}_{\text{crop,mixed}}$ is the yield of the crop in mixture (t ha⁻¹),

$\text{Yield}_{\text{crop,pure}}$ is the yield of the same crop in pure stand (t ha⁻¹), where unfertilised and fertilised specifies if the pure reference stands of oats were fertilised or not,

p_{crop} is the proportion of the crop's sowing density in the mixture relative to its pure stand, and

crop represents either NLL or oat.

Those metrics allowed to compare the mixed cropping system's land use and crop performance relative to their monocropping equivalents. By definition, the LER in pure stands is 1, the CPR of one crop is 1 if a crop does not benefit nor suffer from mixed cropping, and the total CPR of two crops is 2 if the two crops do not interact with each other.

2.5.2 | Modelling

The response variables were analysed using linear mixed-effects models. Four model-classes M1–M4 were designed to suit the target variables (Table S2). The treatment, year, location, and their interaction effects were modelled as fixed effects and the block within a field as a random effect. The models were fitted using the lme4 package within the R programming language (Bates et al. 2015; R Core Team 2025). Inferences were calculated using the lmerTest package, which provides the Satterthwaite degree of freedom adjustment for the type III ANOVA and the contest-function, which was used to test linear contrasts (Kuznetsova et al. 2017). The contrast sum parametrisation was used to allow the interpretability of the regression coefficients to the population mean, and partially fitted intercepts were used for each group in case of the M2 and M4 models (R syntax: 'y ~ 0 + group'). Post hoc pairwise comparisons ($\alpha = 0.05$) were performed to assess varietal differences.

2.5.3 | Robustification

To mitigate the influence of outliers, the outlier weights were automatically adapted using the weights from the analogous model derived by the rlmer function of the robustlmm package (Koller 2016). Target outliers were selected by applying the bounded influence function of Huber loss. This application of the robustification is indicated in the Supporting Information, Appendix A (robustify = TRUE).

2.5.4 | Static Grain-Yield Stability

To assess treatment-level differences in the static grain-yield stability, the coefficient of variation (CV) of the partial NLL, partial oat and the total yield for each treatment were calculated. The CV was computed using the standard deviation and mean of total yield, following the implementation in the metan package (Olivoto 2020). A permutational multivariate analysis of variance (PERMANOVA) was applied for differences among treatments, years and locations on Bray–Curtis distances to compare treatments pairwise (9999 permutations; strata = block) (Martinez Arbizu 2020; Oksanen et al. 2001). p values were adjusted by Benjamini–Hochberg across all pairs.

2.5.5 | Dynamic Grain-Yield Stability

The dynamic grain-yield stability across environments (location × year) was assessed using the univariate Finlay–Wilkinson regression approach, also known as joint regression

(Finlay and Wilkinson 1963). The analysis was implemented performing the regression-based stability analysis according to Eberhart and Russell (1966) (Supporting Information—formulas 1 and 2). The calculated slope coefficient, b_1 , represents treatment responsiveness to the environment. A b_1 slope coefficient close to 1 indicates average responsiveness: The treatment performs proportionally to environmental productivity. Values of b_1 above 1 reflect a more responsive or opportunistic treatment, showing above-average yield under favourable conditions but reduced performance in less productive environments, whereas b_1 below 1 denote a stable or conservative treatment that maintains relatively consistent yield across environments. The calculated Eberhart-Russell deviation variance S_{di}^2 at low levels indicates that the treatment's response to the environment is highly predictable and stable (consistent across environments), whereas a high variance indicates erratic or inconsistent performance across environments, that is, high dispersion of the data points around the slope coefficient b_1 .

To analyse the treatment-by-location interactions, and to quantify the grain-yield stability based on a multivariate model, the additive main effects and multiplicative interaction (AMMI) model was applied (Gauch 1992; Zobel et al. 1988). The AMMI model decomposed the observed total yield response Y_{ij} of treatment i in location j into additive main effects for treatment and location, plus multiplicative interaction effects captured by principal components axes (IPCA):

$$Y_{ij} = \mu + G_i + E_j + \sum_{k=1}^N \lambda_k \gamma_{ik} \delta_{jk} + \epsilon_{ij}$$

where:

μ is the grand mean,

G_i and E_j are the treatment and location main effects,

λ_k is the singular value of the k^{th} interaction principal component axis (IPCA),

γ_{ik} and δ_{jk} are the treatment and location scores for the k^{th} IPCA, and

ϵ_{ij} is the residual term.

Based on the AMMI-model, the weighted average of absolute scores (WAAS) was computed to summarise multidimensional interaction effects into a single stability index, following Olivoto et al. (2019) as implemented in the metan R package (Olivoto 2020):

$$WAAS_i = \sum_{k=1}^N w_k |IPCA_{ik}|$$

where w_k is the proportion of the interaction sum of squares explained by the k^{th} IPCA.

The WAAS summarises the multidimensional treatment-by-location interaction from the AMMI model into a single index of stability. Lower WAAS values indicate smaller absolute

interaction effects and thus higher grain-yield stability, while higher WAAS values denote stronger environmental sensitivity. Together, the b_1 , S_{di}^2 and WAAS indices capture the facets of yield stability: b_1 describes the directional response to the location, S_{di}^2 the dispersion around the direction of the response, and WAAS quantifies the magnitude of interaction-driven variability across locations and years, that is, the treatment's sensitivity to environmental changes.

3 | Results

3.1 | Grain Yield

In Reckenholz, the most productive location, median grain yield of the pure fertilised oat stands ranged between 4.9 and 5.4 t ha⁻¹. Pure NLL stands produced 2.8–3.6 t ha⁻¹, while the NLL x oat mixtures reached 3.7–4.8 t ha⁻¹. Gross Lüsewitz and Seegräben exhibited similar yield to Reckenholz in pure fertilised oat stands; however, the NLL yield and total yield were lower in Gross Lüsewitz ($p < 0.001$). Reckenholz and Seegräben exhibited the highest NLL yield in pure stands compared with the other locations ($p < 0.001$) (Figure 1).

In 2022, the total yield of Bad Vilbel and Novi Sad was lower across all observed treatments than the total yield of Reckenholz, Seegräben or Gross Lüsewitz ($p < 0.001$), whereas in 2023, only the total yield of Gross Lüsewitz was significantly lower than the yield recorded in Novi Sad, Reckenholz and Seegräben (Table S3). Furthermore, the yield of all NLL and oat varieties in pure stands ($p < 0.001$) and the partial yield of Jowisz x Troll in mixed stands differed significantly ($p < 0.05$). Across all locations the average yield of pure NLL and oat stands was not significantly different from the average yield across all mixtures. Regarding the proportion of the partial NLL yield in mixtures, Bad Vilbel and Seegräben exhibited higher NLL than oat proportions of 62% and 59% across all years, respectively, whereas the proportions of the NLL yield in mixtures amounted to 35%, 29% and 24% in Gross Lüsewitz, Novi Sad and Reckenholz, respectively ($p < 0.001$). A strong year effect was apparent, resulting in an elevated proportion of the NLL yield by 16% in 2022 and 7% in 2023 across all mixtures. Additionally, an oat-interaction effect was detected, resulting in an increased NLL proportion by 5% if the NLL were mixed with Troll, and a decreased proportion by -4.6% if the NLL were mixed with Lion. All locations exhibited strong year-by-year variation of the NLL proportion (Appendix A).

3.2 | Grain-Yield Performance

The LER_N assessed across all locations with regards to fertilised oats as pure stands, years and treatments did not differ from unity (LER_N = 1) on a treatment, nor location level (Appendix A). Additionally, no difference could be detected between any pairs of mixed stand treatments or locations. Though the LER with regards to unfertilised oats was higher than the LER_N, it still did not differ from unity (LER = 1). The total CPR with regards to fertilised and unfertilised oats as reference pure stands was elevated above unity ($E = 2$) for all mixed stands, in absence of any treatment effect, amounting to

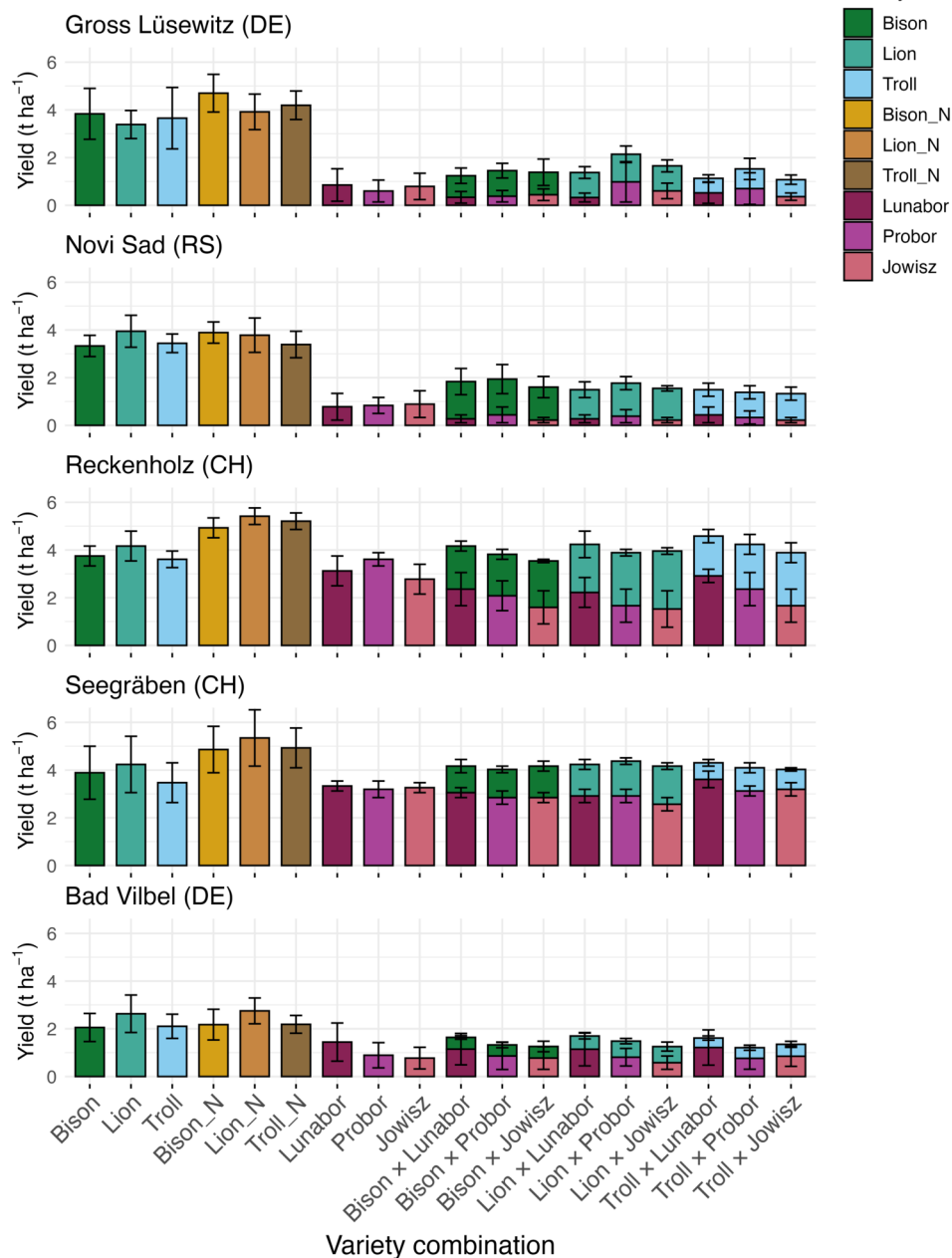


FIGURE 1 | Grain yield overview of pure and mixed stands by location and the location's country code in brackets. Fertilised oats are shown in yellow-brown hues. For all graphs, the median value is represented by the bar height, and the variability (median absolute deviation) by the error bars. Data were pooled across all years. Bars with a single colour represent pure stands. In mixed stands, the lower bar represents the partial lupin values; the upper bar the partial oat values.

an average CPR of 5.3 ($p < 0.001$), and $CPR_N = 4.6$ ($p < 0.001$), respectively, driven by the high oat CPR (Appendix A). The CPR_N was significantly lower than the recorded CPR in all mixed treatments ($p < 0.05$) except for Troll $\times$ Lunabor and Troll $\times$ Jowisz. None of the CPR or CPR_N values exhibited significant differences between treatments across all locations and years. Similar to the total CPR, the CPR_{oat} was above unity ($E = 1$), with regards to both the fertilised (CPR_{oat_N}) and the unfertilised (CPR_{oat}) oats as pure reference stands ($p < 0.001$). The CPR_{oat} was significantly larger than the CPR_{oat_N} for all mixed Bison and Lion treatments ($p < 0.05$),

whereas the mixed Troll treatments were agnostic to the fertilisation regime of their pure reference stands. Post hoc comparisons unveiled significantly higher CPR_{oat} and CPR_{oat_N} in three cases of Lion, compared with Troll, where Lion showed a CPR exceeding the Trolls' CPR by 0.8–0.9 ($p < 0.01$). However, these effects were restricted to specific mixed cropping comparisons (e.g., Lion $\times$ Probor compared with Troll $\times$ Probor) but did not hold true for both oat varieties across all paired mixtures. Conversely to the CPR of oats and the total CPR, the CPR of NLLs did not differ from unity ($E = 1$), and there was no effect of variety, location or year effects.

3.3 | Grain-Yield Stability

3.3.1 | Static Grain-Yield Stability

The static grain-yield stability, expressed as the coefficient of variation (CV) calculated on a treatment basis across all environment-years unveiled no differences in the coefficient of variation across partial NLL, oat yield or the total yield (Table 3). However, trends were visible for the yield variation compared with the treatments' mean yield; the variations were larger in pure stands of NLLs and some mixed stands, relative to the majority of the mixed stands and pure (un-)fertilised oat stands. Furthermore, fertilised and unfertilised oats did not differ significantly with regard to their CV.

3.3.2 | Dynamic Grain-Yield Stability

The Finlay–Wilkinson regression coefficients (b_1) measuring the responsiveness of the total yield to environmental impact was significantly elevated ($b_1 > 1$) in pure stands of fertilised Lion, and the mixed stands of Bison $\times$ Lunabor, Lion $\times$ Lunabor, Lion $\times$ Jowisz and Troll $\times$ Probor, whereas Bison $\times$ Probor and Bison $\times$ Jowisz exhibited a buffering capacity ($b_1 < 1$) to the environmental influence ($p < 0.005$). All pure stands of NLLs and oats, other than fertilised Lion, and the mixed stands of Lion $\times$ Probor and Troll $\times$ Jowisz exhibited average environmental

responsiveness. The Eberhart–Russell deviation variance S_{di}^2 was highest in pure stands of NLLs, and lowest in mixed treatments (Table 3). The pure stand of fertilised Lion and Lion $\times$ Probor both combined high responsiveness b_1 with low S_{di}^2 dispersion, indicating that both treatments reliably and consistently respond to their environmental conditions.

The AMMI model unveiled two groups according to the WAAS-scores: the sensitivity to environmental conditions of unfertilised pure oat stands was higher than that of mixed stands (Figure 2 and Table 3); furthermore, the AMMI-Model unveiled significant location and treatment effects but no interaction thereof (Table S4). The WAAS-scores indicated the mixture's higher stabilities across all environment-years, due to their weaker sensitivity to the location effect. The WAAS scores also indicated a trend towards greater stability in fertilised pure oat stands than in unfertilised pure oat stands, although this difference was not statistically significant. Across the assessed interaction principal components axes (IPCA), IPCA1 distinguished between the two groups of locations Novi Sad and Gross Lüsewitz (negative loadings) versus Bad Vilbel, Reckenholz and Seegräben (positive loadings) (Figure 3). Additionally, IPCA1 clearly distinguished the pure stands of NLLs (positive loadings) from the oats (negative loadings). By contrast, IPCA2 distinguished the fertilised pure stands of oats (negative loadings) from the unfertilised pure stands of oats (positive loadings). With regards to the factor loading of

TABLE 3 | Overview of all grain-yield stability metrics summarised across all locations and all years on a treatment basis. CV = Coefficient of variation, b_1 = Finlay–Wilkinson slope, S_{di}^2 = Eberhart–Russell deviation variance, WAAS = weighted average of absolute scores. Letters correspond to the significance grouping of the pair-wise post hoc tests ($\alpha = 0.05$) adapted for multiple testing. Variety_N represents fertilised pure oat stands.

Treatment	CV total yield (not significant)	b_1 (responsiveness)	S_{di}^2 (dispersion)	WAAS (sensitivity)
Bison	17	0.68a	0.24a	0.66a
Lion	16	0.63a	0.14a	0.58a
Troll	17	0.57a	0.3 a	0.80a
Bison_N	18	1.10 a	0.21a	0.35a
Lion_N	16	1.14b	0.05b	0.08b
Troll_N	15	1.20 a	0.09a	0.15b
Lunabor	31	0.95a	0.22a	0.44a
Probor	35	1.05a	0.23a	0.48a
Jowisz	27	1.01a	0.19a	0.38a
Bison $\times$ Lunabor	17	1.08b	<0.01b	0.11b
Bison $\times$ Probor	18	0.98c	0.03b	0.04b
Bison $\times$ Jowisz	18	0.91c	0.06 b	0.08b
Lion $\times$ Lunabor	15	1.05b	0.03 b	0.21b
Lion $\times$ Probor	16	1.14a	0.09 a	0.34a
Lion $\times$ Jowisz	15	1.05b	0.01 b	0.10b
Troll $\times$ Lunabor	17	1.21b	0.03 b	0.20b
Troll $\times$ Probor	27	1.23b	0.06 b	0.35a
Troll $\times$ Jowisz	24	1.03b	<0.01b	0.07b

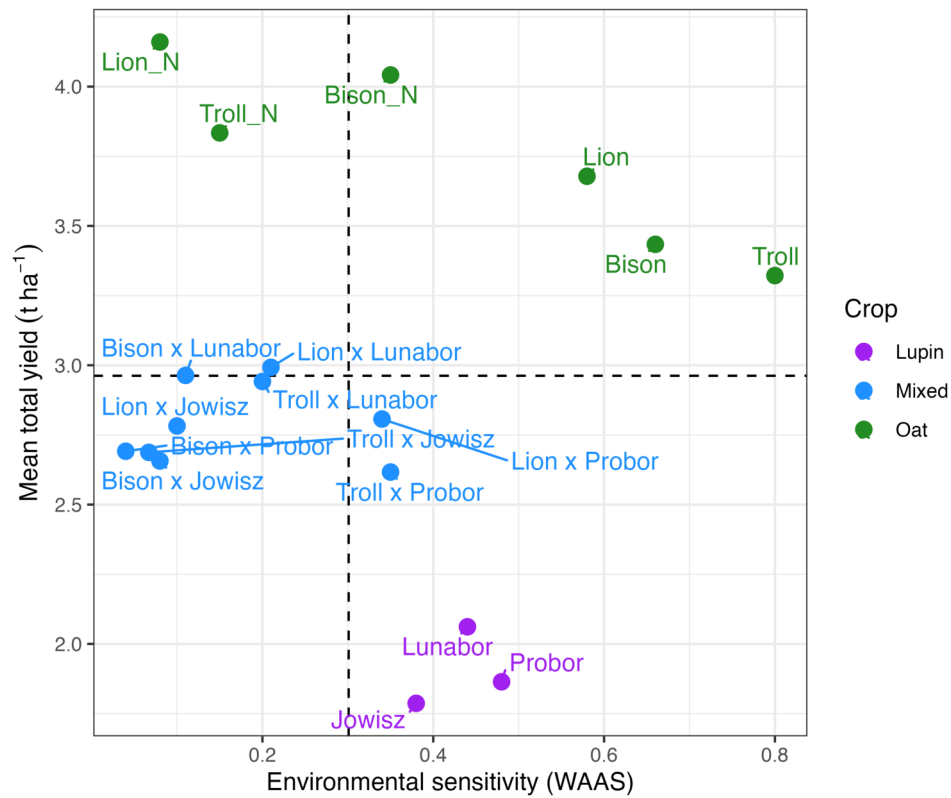


FIGURE 2 | Mean total yield plotted against the weighted average of absolute scores (WAAS), an index of environmental sensitivity, for pure and mixed stands across 2022–2024 (2022–2023 for the Swiss locations). Treatments in the upper left quadrant combine high yield with low sensitivity, whereas points further to the right indicate lower grain-yield stability. Dashed lines mark the median values of both axes.

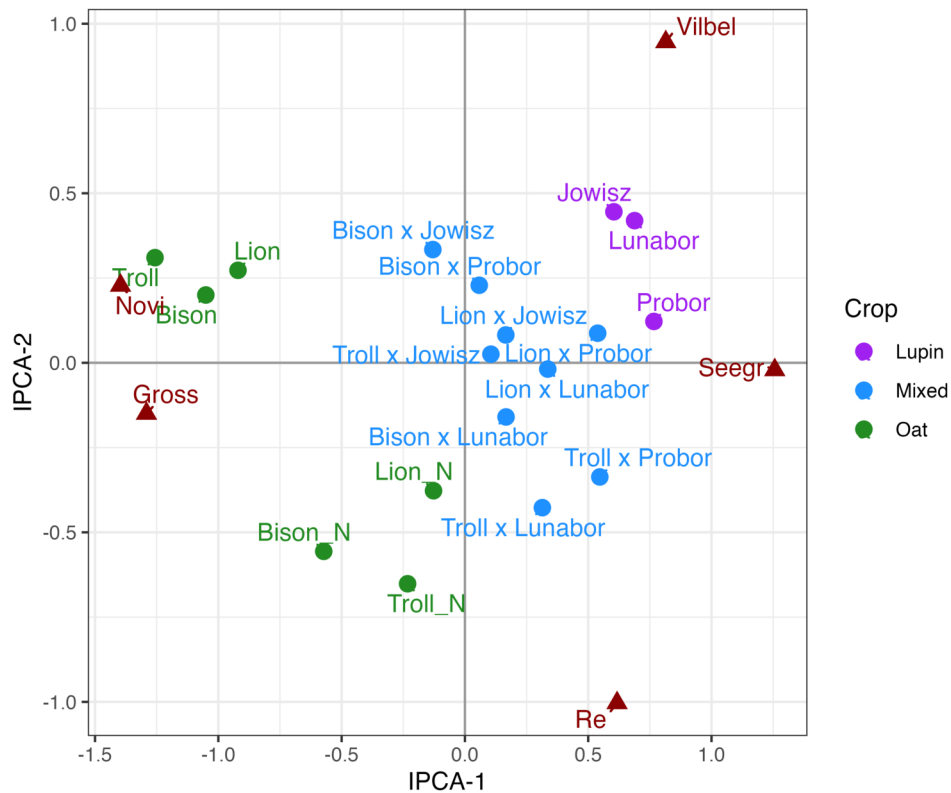


FIGURE 3 | The additive main effects and multiplicative interaction (AMMI) biplot of the treatment (circles) and location (triangles) scores on the first two interaction principal component axes for total grain yield in pure and mixed stands. The closer a treatment is positioned to the origin ($x,y=0,0$), the higher its grain-yield stability. The following location acronyms were used: Gross = Gross Lüsewitz (2022–2024), Novi = Novi Sad (2022–2024), Vilbel = Bad Vilbel (2022–2024), Re = Reckenholz (2022–2023) and Seegr = Seegräben (2022–2023).

IPC1 and IPC2, the two mixtures Lion $\times$ Jowisz and Troll $\times$ Jowisz plotted closest to the origin (0,0). These two treatments interacted least with the locations along IPCA1 and IPCA2, and were thus exhibiting a more stable performance across all five locations than treatments positioned at higher Euclidean distance to the origin (Table S4).

4 | Discussion

The multienvironment evaluation of NLL $\times$ oat mixed cropping demonstrated that total NLL grain yield was maintained across five European locations, while several metrics showed an improved temporal and spatial grain-yield stability relative to the pure stands. The yields recorded in the present study were mostly within the range reported for other European pulse $\times$ cereal mixed-cropping systems, although direct comparisons should be interpreted with great caution because the species combinations, environments, and management conditions differed between studies. For oat-based mixed crops, mean yields of around 3.1 t ha⁻¹ have been reported for oat-vetch systems in Germany and Sweden and for oat-pea systems in Germany (Engbersen et al. 2021; Munz et al. 2023), which is comparable to the yield range observed at Reckenholz and Seegraben in the present study. By contrast, the other locations showed lower total yields across both pure and mixed stands, consistent with the yield levels reported by Wang et al. (2012) for lentil-oat mixed crops in Germany. Because these lower yields occurred consistently across all pure and mixed treatments at the respective locations, they are more plausibly attributed to environmental than to varietal effects: this in line with Brooker et al. (2024), that showed a strong influence of rainfall and crop management on the mixed cropping performance. Overall, the yield levels observed in the present study are in agreement with the broader European synthesis by Bedoussac et al. (2015), who reported a mean mixed crop grain yield of 3.3 t ha⁻¹ across 58 pulse $\times$ cereal mixtures.

The productivity indices allow for a clear distinction between land use efficiency and crop performance: Although the LER did not differ significantly from unity, this does not imply an absence of benefits associated with mixed cropping. Rather, it indicates that, on a land-area basis, the mixtures matched on average the reference pure stands, while the responses of the companion crop within the mixtures were asymmetric: This asymmetry was captured by the CPR: namely the oat CPR and the total CPR were consistently above unity and the CPR of the NLL remained unchanged. This suggests that the oat crop captured additional resources without decreasing the NLL performance. This interpretation aligns with the findings of Zustovi et al. (2024), who demonstrated that mixed cropping indices capture distinct aspects of performance and exhibit different responses to crop ratio and total sowing density. Accordingly, in a pulse-centric replacement design as in the current study, the CPR, an indicator accounting for sowing proportion, is more sensitive than the LER to gains of the minority component.

In the present study, yield maintenance was achieved through a flexible contribution of the two partners rather than through a fixed proportion: the NLL ratio in mixtures ranged from 24% in Reckenholz to 62% in Bad Vilbel. Similar weather- and

location-dependent shifts in pulse $\times$ cereal contributions have been reported for oat-vetch mixtures, underlining that the value of mixed cropping lies in partner compensation across environments rather than in fixed crop species proportions (Bedoussac et al. 2015; Brooker et al. 2024; Pużyńska et al. 2021). This yield-stabilising effect of mixed cropping likely reflects niche complementarity and mutual yield buffering, whereby NLL and oat exploit different resources, thus increasing overall resource-use efficiency (Demie et al. 2022; Hauggaard-Nielsen et al. 2001; Jensen 1996). Additionally, in the pulse-centric NLL $\times$ oat mixed cropping system, a strong buffering capacity has been reported, where the respective yields of NLL and oat were negatively correlated, thus jointly buffering yield fluctuations compared to pure stands (Schlup et al. 2026). This pronounced niche complementarity in oat, reflected by its elevated CPR, together with yield buffering between the two species, likely explains the greater grain-yield stability of the mixtures across all environment-years.

Using either fertilised or unfertilised oat pure stands as the reference for LER led to the same conclusion: LER did not differ between baselines. This lack of response to fertilisation likely reflects the high spatiotemporal yield variability across environment-years and the low oat proportion in the mixtures, which reduces its contribution to the total LER, thus limiting statistical power. Different mixed cropping indices respond differently to crop ratio and sowing density (Zustovi et al. 2024), explicitly LER did not elucidate a fertiliser effect, whereas the CPR did; both the total CPR and oat-specific CPR were higher when mixtures were benchmarked against unfertilised oat stands, revealing a fertiliser-mediated gain in the performance of pure oat stands. Because CPR explicitly scales yields by the sowing proportion of each crop, it provides a proportion-corrected measure and is therefore more sensitive to management effects under imbalanced mixtures than the LER. These findings are consistent with the study of Baxevanos et al. (2020), who showed that using unfertilised pure stands as references can yield larger estimates of mixed cropping advantage than using fertilised references.

While the static metric (CV) did not detect significant differences in grain-yield stability, the two dynamic approaches, the Finlay-Wilkinson slope (b_1) and the WAAS, revealed clear contrasts among treatments. In pure stands, fertilised oat Lion combined an above-average responsiveness to environments (slope $b_1 > 1$) with low dispersion around the regression, indicating a predictable response in both favourable and unfavourable conditions. Fertilisation enhanced the stability of oats in pure stands: Fertilised Lion and Troll showed significantly lower WAAS scores than their unfertilised counterparts, which is consistent with the findings of Silva et al. (2016). Most mixed stands exhibited elevated responsiveness to the environmental conditions ($b_1 > 1$), while the most stable mixed treatments exhibited average responsiveness ($b_1 \approx 1$), coupled to low sensitivity to the environmental conditions (low WAAS values). Such stability in pulse $\times$ cereal mixtures is commonly attributed to differential species responses and complementarity that buffer environmental variation and reduce $G \times E$ interactions, resulting in more stable yield among selected combinations (Raseduzzaman and Jensen 2017). Across all mixtures, the LER remained close to one, while the oat-specific and total CPR consistently exceeded one, indicating a mixed-cropping advantage that was largely

independent of variety combination. This reinforces the evidence that the overall mixed-cropping effect outweighs cultivar-specific effects, as reported for barley-pea mixtures and for maize-cowpea mixtures (Hauggaard-Nielsen and Jensen 2001; Watiki et al. 1993). The pattern of varying grain-yield stability gains across the investigated mixtures demonstrates that elevated grain-yield stability was not only a mixed-cropping effect but also depended on the specific pairing of NLL and oat varieties. Similar variety-specific differences have been reported in other pulse $\times$ cereal mixed systems, where mixture performance depended on the complementarity between partners and their responses to resource availability (Weih et al. 2021). Mechanistic work in oat-NLL mixtures further suggests that such variability arises from differences in temporal matching of crop traits, including early vigour, competitive ability, and the timing of resource capture (Engbersen et al. 2021). Thus, optimising grain-yield stability in pulse $\times$ cereal production requires both recognising the general benefits of mixed cropping and exploiting variety-specific interactions that enhance mixture performance.

The increased dynamic grain-yield stability observed for mixed cropping in this study extends the findings of Weih et al. (2021) by showing that under a pulse-centric replacement design (NLL $\times$ oat), mixture stability did not only match but surpassed the pure-crop benchmarks on dynamic grain-yield stability. This pattern also reaffirms the findings by Raseduzzaman and Jensen (2017), who showed that replacement-designed cereals $\times$ pulse mixtures elevate the grain-yield stability across environments. Notably, Bison $\times$ Probor and Troll $\times$ Jowisz were among the most stable mixtures, despite neither corresponding pure stands being highly stable, indicating that stability must be evaluated at the mixture rather than the pure stand level. By quantifying stability using complementary dynamic metrics (Finlay–Wilkinson slope, b_1 , and WAAS), this study demonstrates that the stability advantage of mixtures extends beyond balanced combinations to replacement designs that favour the pulse component.

5 | Conclusions

This study assessed the grain-yield performance and stability of pulse $\times$ cereal mixed cropping compared with pure stands across multiple locations and years. The patterns observed in the present study demonstrate that optimal variety mixtures improve grain-yield stability of both NLL and oat while maintaining crop performance and land use, highlighting their potential for tailoring mixtures to different agri-environmental risks. Importantly, the robust yield-stability advantage of mixtures across environment-years, despite up to six-fold differences in yearly precipitation, suggests that mixed cropping can effectively buffer against increasing climate variability. This supports policy efforts aimed at increasing the production of plant-based proteins. Hence, strategic variety pairing within mixed cropping emerges as an effective approach to combine high crop yield and maintain land use performance while improving the overall cropping systems' resilience and mitigating the pulses' yield instability. Future studies should address the economic effect of increased grain-yield stability, as well as the grain quality and food safety of these pulse $\times$ cereal cropping systems.

Author Contributions

Yannik Schlup: conceptualization, investigation, data curation, formal analysis, methodology, project administration, resources, software, visualization, writing – original draft, writing – review and editing. **Vesna Župunski:** conceptualization, investigation, data curation, project administration, resources, writing – review and editing. **Radivoje Jevtić:** conceptualization, data curation, investigation, project administration, resources, writing – review and editing. **Selma Schurack:** conceptualization, data curation, investigation, project administration, writing – review and editing, resources. **Matthias Heinrich Herrmann:** conceptualization, data curation, investigation, project administration, writing – review and editing, resources. **Andrea Gallehr:** conceptualization, data curation, investigation, project administration, writing – review and editing, resources. **Kathrin Neubeck:** conceptualization, data curation, investigation, project administration, writing – review and editing, resources. **Annette Haak:** conceptualization, data curation, investigation, project administration, writing – review and editing, resources. **Lukas Graz:** writing – review and editing, formal analysis, visualization, software. **Johan Six:** writing – review and editing, project administration, funding acquisition, methodology. **Susanne Vogelgsang:** conceptualization, funding acquisition, resources, writing – review and editing, methodology, project administration.

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Disclosure

During the preparation of this work, the authors used GPT-4 (OpenAI, California, USA) to improve the structure and efficiency of the code to produce figures and GPT-o3pro (OpenAI, California, USA) in support of writing the abstract, introduction and discussion. After using this tool/service, the authors reviewed and edited the content as needed and took full responsibility for the created content.

Data Availability Statement

The data and code supporting the findings of this study are available at the project's GitHub repository (<https://github.com/yannikschlup/lupin-oat-grain-yield-stability>) and are permanently archived on Zenodo under DOI <https://doi.org/10.5281/zenodo.22877423>; all materials are released under the MIT License.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Table S1:** Field characteristics and husbandry measures per location and year (environment-year). **Table S2:** Statistical models deployed to analyse the data. The characteristics explain the details of the model. Each response variable (attribute) in the present study was analysed with one or more of the models listed in the table. To analyse the effect of canopy height difference onto the narrow-leaved lupin proportion and the total yield, model M3 was adapted replacing the predictor treatment with canopy height difference. **Table S3:** Year $\times$ location median yields and median absolute deviations (t ha^{-1}) aggregated across blocks. **Table S4:** The additive main effects and multiplicative interaction (AMMI) model output. **Appendix S1:** Supporting Information.