Field Crops Research 333 (2025) 110083

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Performance of soy-winter wheat relay intercropping under various water conditions

Jennifer B. Thompson [a,b,*], Thomas F. Döring [c], Sonoko D. Bellingrath-Kimura [a,b], Jing Yu [a], Moritz Reckling [a,d]

[a] Leibniz Centre for Agricultural Landscape Research (ZALF), Eberswalder Straße 84, Müncheberg 15374, Germany
[b] Faculty of Life Science, Thaer-Institute of Agricultural and Horticultural Science, Humboldt-University of Berlin, Berlin 14195, Germany
[c] INRES-Agroecology and Organic Farming Group, University of Bonn, Bonn 53121, Germany
[d] Department of Crop Production Ecology, Swedish University of Agricultural Sciences (SLU), Uppsala, Sweden

ARTICLE INFO

Keywords:
Crop diversification
Crop competition
Irrigation
Water stress
Mixed cropping

ABSTRACT

Context: Relay intercropping can increase yields, grow two crops per year in regions where only one is possible, and provide ecological benefits. Nevertheless, relay intercropping is uncommon in Europe and its suitability as a crop diversification strategy is unknown.
Objectives: Using a three-year field trial in eastern Germany, this study sought to understand under which management the system is most viable and how competition for light and water affects yields.
Methods: We studied soy-winter wheat relay intercropping in a plot trial with three cropping systems (sole wheat, sole soy, and relay intercropping), two winter wheat varieties, and two irrigation treatments (irrigated and rainfed). We measured yield, crop biomass, soil moisture, and intercepted photosynthetically active radiation throughout the growing season.
Results: We found that in two of the three experimental years, relay intercropped soy had low or no yield and that the land equivalent ratio (LER) of the system barely reached 1 under any treatment. Water stress negatively affected intercropping as winter wheat outcompeted the soy and the growth-stunted soy received only 40–80 % of the PAR sole soy received. Even after the wheat harvest, intercropped soy did not fully recover and reached 80 % of the sole soy biomass in the best case, but in some years 0–40 %.
Conclusion: Using vigorous winter wheat and narrow-row management for productivity appears to cause water stress in soy. Future research should focus on mitigating water competition and identifying arrangements and varieties adapted to competition.

1. Introduction

Increasing crop diversity with intercropping is a strategy to combat some of the negative environmental externalities of agriculture due to the increased diversity and phenological complementarity of mixed crops. Intercropping frequently has higher productivity than sole cropping stands of the same area (Li et al., 2023; Li et al., 2014; Li et al., 2011; Yang et al., 2015, 2017) and can support ecological benefits on farms (Beillouin et al., 2021; Cong et al., 2015; Letourneau et al., 2011; Lopes et al., 2016). Despite this, intercropping in the EU is uncommon with, for example, only 13 % of German farmers utilizing intercropping of cash crops (Bonke and Musshoff, 2020). Common obstacles to intercropping reported by farmers include unstable yields, lack of machinery for harvesting and separating mixtures, contracts with strict quantity and quality regulations, and lack of technical support (Bonke and Musshoff, 2020; Himanen et al., 2016; Mamine and Farès, 2020). Thus, finding intercropping management that circumvents some of the barriers to farmers, including the additional cultivation and sorting machinery, may be necessary to increase adoption.

Relay intercropping involves growing two or more crops that do not completely overlap in their growing season and can increase productivity compared to sole cropping (Sandler et al., 2015; Wang et al., 2022). In relay intercropping, a second crop is planted between the existing rows or strips of the standing crop (Fig. 1). After a period of co-growth, the first crop is harvested and the second crop can recover from the period of resource competition and fill the space where the first

* Corresponding author at: Leibniz Centre for Agricultural Landscape Research (ZALF), Eberswalder Straße 84, Müncheberg 15374, Germany.
E-mail address: jennifer.thompson@zalf.de (J.B. Thompson).

https://doi.org/10.1016/j.fcr.2025.110083
Received 10 January 2025; Received in revised form 6 June 2025; Accepted 21 July 2025
Available online 28 July 2025

crop stood (Chen et al., 2024; Li et al., 2001). Relay intercropping is thus both a temporal and spatial diversification strategy which maintains continuous cover on the field and allows for two crops where double cropping may be risky (Simon-Miquel et al., 2023). Relay cropping can generally be managed with conventional farm machinery without the need for post-harvest sorting due to separate harvests, meaning it can have a lower barrier to entry than other mixed cropping systems. Nevertheless, the simultaneous cultivation of two crops can pose additional management challenges including weed management, input usage, and row spacing optimization to maximize plant interactions while minimizing competition (Lamichhane et al., 2023)

Yield increases in relay intercropping compared to sole crops can be attributed to positive interactions between the component crops (Chen et al., 2018; Homulle et al., 2022; Sun et al., 2019). Ecological processes such as resource complementarity, facilitation, and competition play crucial roles in determining the success of intercropping (Duchene et al., 2017), especially in relay systems which need to be managed for multiple crops using resources at different times. Facilitation can occur when one species positively affects another by changing the abiotic or biotic environment allowing access to additional resources. This can materialize as soil nutrient mobilization in which one crop fixes nitrogen or uses root exudates to mobilize nutrients which ends up benefiting the neighboring species (Sun et al., 2019; Zhang and Li, 2003). Alternatively, relay intercropping can benefit from resource complementarity, in which the component crops use different resource pools across time and space, increasing resource use efficiency. Resource complementarity can occur when cultivating crops with different root architecture or resource niches; for example, a shallow and deep rooting species can extract soil water from different soil depths at different times (Chen et al., 2018; Zhang et al., 2022). Understanding how crops interact in terms of light, water, and nutrient use can help optimize the benefits of relay cropping. Some amount of resource competition is likely unavoidable during the co-growth stage of relay intercropping and can be detrimental to the system, especially the yield of the second crop. Therefore, localized and crop specific studies are needed to understand if and how a system can be managed successfully depending on specific resource availability.

Relay intercropping of winter wheat and soy is a potentially interesting crop combination due to its functional diversity and complementarity from a cereal and grain legume. Winter wheat has high nitrogen needs while soy fixes nitrogen, allowing for lower N fertilization than in a typical wheat field as the soy does not need to be fertilized. Moreover, while the system's season can span an entire year (winter wheat planted in the fall and soy harvested in the fall), the co-growth stage is approximately only two months, showing high temporal complementarity for resources which could alleviate resource competition. Some studies have found that soy is less sensitive to water stress pre-flowering and water availability only becomes critical for yield at pod filling (Morrison et al., 2006), which is after the co-growth period. Wheat also has lower water requirements at the end of the co-growth stage to ensure adequate senescence and grain drying. As for light needs, researchers found two peaks of intercepted radiation throughout the growing season of soy-wheat relay intercropping, one for each crop, with a period of low use in between, leading to an overall higher light use efficiency than sole crops (Caviglia et al., 2004).

Relay intercropping of winter wheat and soy may have high yield potential in central Europe, where winter wheat is already a well-established, high-yielding crop (FAOSTAT, 2024). While soy is a relatively new crop in central Europe and especially northeastern Germany, there is growing interest in domestic legume production and substantial opportunities for expanding European soybean cultivation (Kuepper and Riemersma, 2019). This system presents a new approach for farmers to integrate a newer crop alongside an established, high-performing one. Intercropping wheat with soy has been shown to be successful in the US (Duncan and Schapaugh, 1997; Sandler et al., 2015; Wallace et al., 1996), Pakistan (Raza et al., 2023), and China (Wang et al., 2022). However, the applicability of these benefits to other regions remains uncertain as management practices are highly variable between regions and irrigation, farm machinery, input usage, and varieties used can all vary due to local practices, regulations, and climatic conditions.

Utilizing a three-year plot trial, we studied the effects of two winter wheat varieties and irrigation management on yield and crop development in a soy-winter wheat relay intercropping system in eastern Germany. We aimed to answer the research questions a) can soy-winter wheat relay intercropping produce yields as high as sole cropping? b) Under which management conditions is this possible? c) Is there potential critical light and water competition during the co-growth phase that can explain the resulting yields and can soy recover from this period? We hypothesized that the relay intercropping would overyield compared to the sole crops due to increased resource utilization and a longer growing season. We additionally hypothesized that yields would be higher in irrigated systems and with the shorter wheat variety as there would be less water and light competition.

2. Materials and methods

2.1. Experimental setup

Soy-winter wheat relay intercropping trials were conducted at the Experimental Field Station of the Leibniz Center for Agricultural Landscape Research (ZALF), Müncheberg, Germany, 50 km east of Berlin (52°31’N, 07°38’E), over three growing seasons (harvest years

Fig. 1. Phases of soy-wheat relay intercropping. a) The established first crop, winter wheat, with empty rows for the second crop, b) soy seedlings in between wheat, c), fully ripe wheat with the growing soy, and d) wheat that has been harvested leaving the growing soy.

2021–2023). Soils in the region are sandy loams formed from glacial deposits. The average soil texture for the 3 experimental years was 69 % sand (range 64–72 %), 6 % (range 5–8 %) clay, and 25 % silt (range 23–28 %) so a sandy loam. The long-term average annual temperature is 9.0 °C with an average annual precipitation of 600 mm. Monthly precipitation, evapotranspiration, and temperature data were collected on station. Monthly water deficits were calculated as the monthly average precipitation amount minus the monthly average evapotranspiration amount. Cumulative deficits were calculated by starting in January then adding (or subtracting) subsequent months. Negative values indicate a deficit where evapotranspiration exceeded precipitation.

Our experiment consisted of a randomized, blocked plot trial with three cropping treatments (sole wheat, sole soy, and relay intercropping), two irrigation treatments (rainfed and irrigated), and two wheat variety treatments (var. Moschus and RGT Reform, hereafter, Reform) for a total of 10 treatments. Supplementary irrigation was scheduled to avoid severe drought but not to provide a situation of unlimited water as this would be highly infeasible for farmers in the region (Table 1). There were 6 replicates and the plot size was 3 × 8 m. A 50 cm buffer strip of wheat was left between all plots apart from sole soy plots which had adjacent, unfertilized wheat plots as buffers to minimize effects (e.g. from nitrogen fixation or fertilization) on neighboring plots. Wheat was planted with a row distance of 12.5 cm, 2 cm deep at 416 seeds m^{-2}. For soy-wheat relay intercropping, the wheat was planted in alternating 12.5 cm double rows with a 37.5 cm gap for soy. Sole soy was sown in 37.5 cm rows with a density of 70 plants m^{-2} at 3–4 cm depth. Intercropped soy was seeded with the same density and row distance as the sole crop and a shallow sowing depth of around 2 cm when winter wheat was in the tillering stage and before stem elongation to avoid damage by the tractor wheels. This means the total relative crop density for intercropped plots was 150 % (100 % soy + 50 % wheat density). All crops were managed conventionally with mineral fertilization for wheat and pesticides for both crops (Table 1). We gave 100 kg to the sole crop wheat (2 doses) and 60 kg to the wheat in intercropped plots (1 dose). N fertilization in the intercropped plots was only given as one dose in early spring before soybean was sown to prevent any negative effects on biological nitrogen fixation by soy. The first N treatment in March (and the only one for intercropping) was equivalent in sole wheat and intercropped plots so that the wheat had the same resources available before soy sowing. Plots received irrigation in the late spring and summer following soy irrigation schedules with overhead irrigation. Wheat straw was left on the field until the end of the trial.

2.2. Crop development

We tracked crop growth and resource availability by measuring intercepted photosynthetically active radiation (PAR), soil moisture, and crop biomass at key points in the growing season. Soy was measured at BBCH 13 (first trifoliate leaf), 61 (beginning of flowering), 71 (beginning of pod development), and 89 (pods fully ripe). We measured wheat at BBCH 31 (first node), 61 (beginning of flowering), 71 (watery ripe grain), and 89 (fully ripe grain). PAR was measured with a SS1 Canopy Analysis System (SunScan). The fraction of transmitted PAR for intercropped soy was measured above the soy canopy level and compared to the PAR received at the top of the sole soy canopy level. Soil moisture was measured in the 0–7 cm topsoil with a soil sensor (Delta-T Devices ML3 ThetaKit HH2 Moisture Meter and ML3 sensor in 2021–2022 and Acclima SDI-12 Sensor Reader RD1200 in 2023) 3 times per plot per sampling. Moisture was always measured in between rows of crops. We collected a 0.5 m^2 quadrat of total aboveground biomass from 3 plots per treatment during the growing phases and from every plot at harvest. Due to the small number of observations during the growing season (n = 3), we did not perform a statistical analysis of biomass data.

2.3. Harvest measurements

At the end of the growing season, plots were harvested with a combine harvester. To avoid edge effects in the border rows and areas where biomass was sampled on one end of the plot, yields were taken from 14 m^2 of the plot's total 24 m^2. Relay wheat was harvested with the addition of a combine attachment (Flexxifinger, Canada) that pushed the young soy down while wheat was harvested above it. 86 % dry weight grain was calculated. Samples were dried at 60°C and subsequently weighed then ground and analyzed for NPK with an elemental analyzer. Grain protein for soy and wheat was estimated by multiplying grain %N by 5.5 (Mariotti et al., 2008). NPK data was only used for protein calculations, but the entirety of the data is reported in the Supplemental Materials.

2.4. Statistical analysis

We calculated land use equivalent ratios (LER) with the following formula

Table 1
Management of the 3 cropping systems.

	Sole wheat	Soy-wheat relay intercropping	Sole soy
Tillage	Previous crops were cereals. All plots plowed at a 23 cm soil depth with a mouldboard plough in early October		
Seedbed preparation	Leveled to 10 cm with a cultivator		Cultivated to 5 cm
Sowing	18.11.2020 14.10.2021 29.09.2022	Same as sole crops	06.05.2021 29.04.2022 15.05.2023
Fertilization	60 kg/ha N, 14 kg/ha S in March. 40 kg/ha N, 10 kg/ha S in April	60 kg/ha N and 14 kg/ha S in March	No fertilization
Herbicides	Carmina 640 (1.50 l/ha) was applied at BBCH 11 in a broth of 600 l/ha. The growth regulator Acucel (1.00 l/ha) was applied on the same plots in a 400 l/ha broth at BBCH 30 2021: Fungicide Opus Top (250 g/l Fenpropimorph, 84 g/l Epoxiconazol) applied at BBCH 69 2022 + 2023: Fungicide Elatus (75 g/l Benzovindiflupyr, 150 g/l Prothioconazol) and Sympara (125 g/l Prothioconazol, 125 g/l Tebuconazol) applied at BBCH 31		Pre-emergence herbicides (Centium 36 CS 0.25 l/ha, Sencor Liquid 0.30 l/ha and Spectrum 0.60 l/ha) applied BBCH 03 in a 600 l/ha broth. Post emergence herbicide (Fusilade MAX, 2.00 l/ha) applied in 600 l/ha broth.
Irrigation	Irrigated plots received 110–230 mm (over 8–10 events) during summer. 150, 80, and 80 mm irrigation was applied during the co-growth time (May-July) and 80, 40, and 40 mm during the recovery phase (August) in 2021, 2022, and 2023, respectively.		
Harvest	11.08.2021 21.07.2022 24.07.2023	Harvested with a FlexxiSelect combine header attachment (Flexxifinger). Same dates as sole soy except in 2022 (08.11.2022)	27.10.2021 12.10.2022 11.10.2023

$$LER = \frac{Yield_{IS}}{Yield_{SS}} + \frac{Yield_{IW}}{Yield_{SW}}$$

where IS and IW are intercropped soy and wheat and SS and SW are sole soy and wheat, respectively. A partial LER for intercropped wheat to determine under or overyielding was calculated with just the wheat terms of the equation. To determine if the intercropped wheat yield was significantly different than the expected yield based on seeding densities (0.5) we used a one-sample *t*-test. The transgressive overyielding index was calculated based on the following formula (Li et al., 2023):

$$TOI = \frac{(Yield_{IS} + Yield_{IW})}{\max(Yield_{SW}\quad,\quad Yield_{SS}\quad)}$$

Yield, PAR, and soil moisture data were analyzed with linear mixed effects models with the R package *lme4*. For yield and PAR analysis, irrigation, year, and cropping treatment were set as interacting, fixed effects and block as a random effect. Soy and wheat yields were analyzed separately. As we found a significant effect of year, each year was then analyzed separately due to high variation in climatic conditions between years to best understand the effect of cropping and irrigation treatment on yields. There was no significant interaction between irrigation and cropping treatment for yields, so it was removed from the model.

Residuals versus fitted values and normal quantile–quantile (QQ) plots were used as model diagnostics to assess normality of residuals and homogeneity of variance. Tukey HSD post-hoc tests were used to determine variable level differences on statistically significant variables ($p < 0.05$) with the *emmeans* package. In models with many interacting levels (e.g. month and cropping treatment), marginal means were calculated to see treatment effects within a level, e.g. the effects of cropping treatment within a month rather than pairwise comparisons between months. Data was square root or log transformed if needed to meet model assumptions, but all plots show untransformed means. All data was analyzed in R (v4.4.1; R Core Team, 2024).

3. Results

3.1. Climatic conditions

Climatic conditions varied strongly between the three experimental years (Fig. 2). The yearly precipitation was 513, 362, and 676 mm for 2021, 2022, and 2023, respectively. 2022 was the only experimental year where monthly precipitation levels of pre-soy drilling (Jan-Apr) did not reach historical averages. The average historical yearly temperature is 9.33 °C. In 2021 we saw an average of 9.5 °C and an average of 10.5 °C in 2022 and 2023 (Fig. 2). The total yearly water deficit for 2021 was −211 mm, −443 mm in 2022, and −58 in 2023. When looking at the cumulative water deficit starting in January, the water deficit in July (soy flowering) was −221, −346, and −128 mm in 2021, 2022, and 2023 while the actual monthly water deficit for July was −80.6, −106.4, and −61.2 mm.

3.2. Soil moisture

Shallow soil moisture levels (0–7 cm) varied strongly during the cropping system in each of the three experimental years (see supplemental materials for seasonal patterns). At the time of soy planting, soil water moisture was approximately 15 % in 2021 and 2023 but only around 7 % in 2022, below our soil's approximate permanent wilting point of 7.9–9.1 % soil moisture (Rab et al., 2011; Salter and Williams, 1965). We found no significant difference in soil moisture between treatments at the time when soy was sown.

3.3. PAR

We found a significant effect of irrigation and a month*irrigation interaction on the fraction of PAR transmitted to intercropped soy in 2021 (p_{irr}=0.015, p_{irr*mo}=0.014 ; Fig. 3) and 2023 (p_{irr}=0.022, p_{irr*mo}=0.035) but no significant effects of irrigation in 2022. Reform relay soy received significantly more transmitted PAR, 6 % on average, than Moschus relay soy in 2021 ($p = 0.028$). In 2023, soy intercropped with Moschus received significantly more PAR than soy intercropped with Reform ($p < 0.0001$), approximately 16 % higher averaged over irrigation and month. Relay soy received the highest proportion of PAR in 2023, up to nearly 80 % of sole soy, and the relay soy was also the tallest in this year (Supplemental Materials).

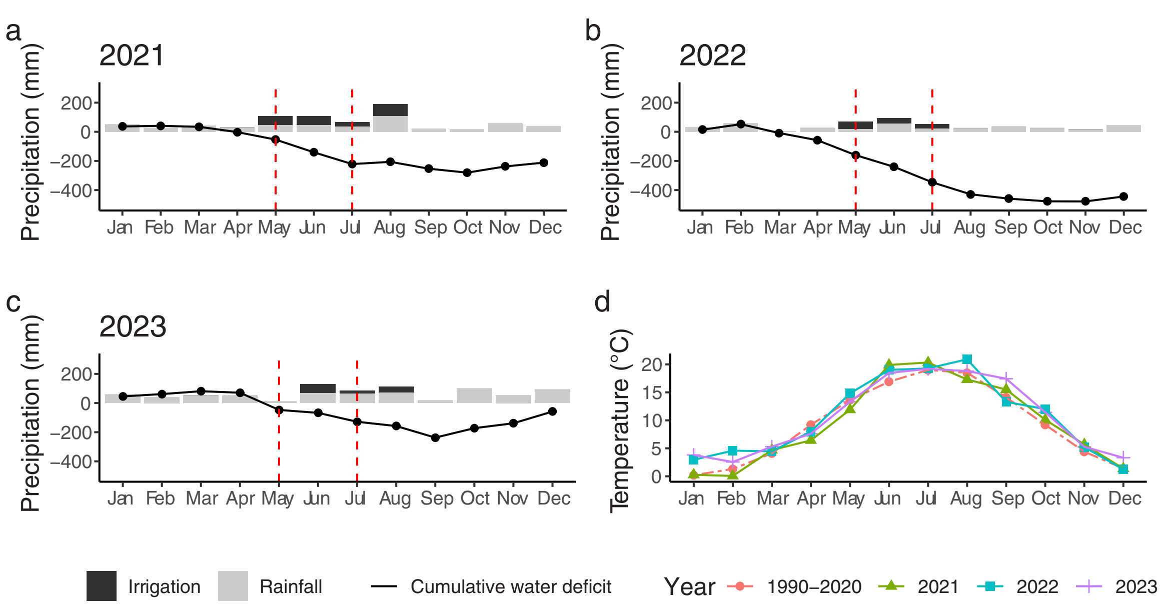

Fig. 2. Climatic data from the three experimental years showing precipitation and irrigation levels from a) 2021, b) 2022, c) 2023 and d) average monthly temperatures for all time periods. The cumulative water deficit is calculated without irrigation. In panels a-c the red, dashed lines indicate the approximate periods of co-growth in intercropping.

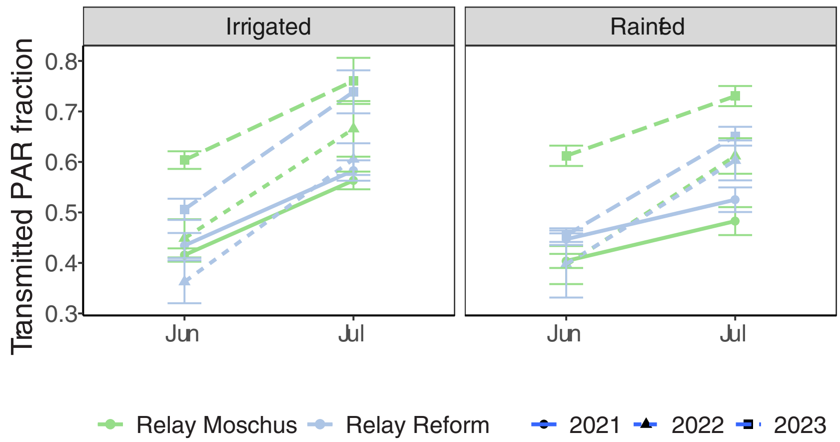

Fig. 3. The fraction of PAR transmitted to the intercropped soy canopy: PAR received by the sole soy canopy during the co-growth period.

3.4. Biomass development

Despite the 50 % reduction in wheat planting density in the relay treatment, by the end of the growing season, relay Reform reached 76–97 % of the sole Reform biomass in irrigated plots and 83–97 % in rainfed plots depending on the year (Fig. 4). Relay Moschus reached 78–81 % of the sole Moschus in the irrigated plots and 62–92 % in the rainfed plots. Soy biomass was always higher in sole soy than the relay soy treatments (Fig. 4). Relay soy biomass recovery after wheat harvest varied strongly between years (Fig. 5) as in 2022 there was little to no recovery, whereas in 2023 the relay soy biomass reached nearly 80 % of the sole soy biomass (Fig. 6). Differences between soy in Moschus versus Reform relay systems were small.

3.5. Yields

We found that wheat grain yields were significantly different between years ($p < 0.0001$; Fig. 7), cropping treatment ($p < 0.0001$), and irrigation ($p < 0.0001$), and there was a significant interaction between treatment and year ($p < 0.0001$) and irrigation and year ($p < 0.0001$) but no other interactions. Irrigated wheat yielded significantly higher than rainfed wheat in 2021 ($p = 0.0003$) and 2022 ($p < 0.0001$; Fig. 7) but there was no irrigation effect in 2023. We also found significant effects of the cropping system on wheat yields every year. Both relay treatments always yielded significantly less than both sole wheat treatments ($p < 0.0001$ for all years) with relay Reform treatments reaching 49–65 % of the sole Reform yield and relay Moschus reaching 22–66 % of the sole Moschus yield. Relay Reform yielded significantly more than relay Moschus in 2022 ($p = 0.042$) and 2023 ($p < 0.0001$). In 2021 and 2022, both irrigated and rainfed intercropped Moschus overyielded as its partial LER was significantly higher than 0.5 (the expected value based on seeding densities) but underyielded in 2023 (Supplemental Materials). Irrigated Reform overyielded in 2021 and 2022 but did not have significantly higher or lower than expected yields in 2023.

Irrigated soy had significantly higher grain yields than rainfed soy in 2021 ($p < 0.0001$) and 2023 ($p < 0.0001$) but there was no significant interaction between cropping treatment and irrigation. In 2022, nearly all soy plants in the relay treatment died and were not harvestable. Due to the failed treatments and a lack of treatment comparison for the irrigation level, for 2022 we only compared the irrigated treatments. Soy intercropped with Reform and Moschus yielded lower than sole soy every year, approximately 56–100 % less. However, intercropped Reform soy and intercropped Moschus soy yields were not different in 2022 ($p = 0.071$) or 2023 ($p = 0.95$). In 2021, rainfed relay treatments were not significantly different ($p = 1.00$) but in the irrigated treatment, the relay Moschus soy yield was lower than relay Reform soy ($p = 0.02$).

For relay systems, we found a tradeoff in soy and wheat grain yields

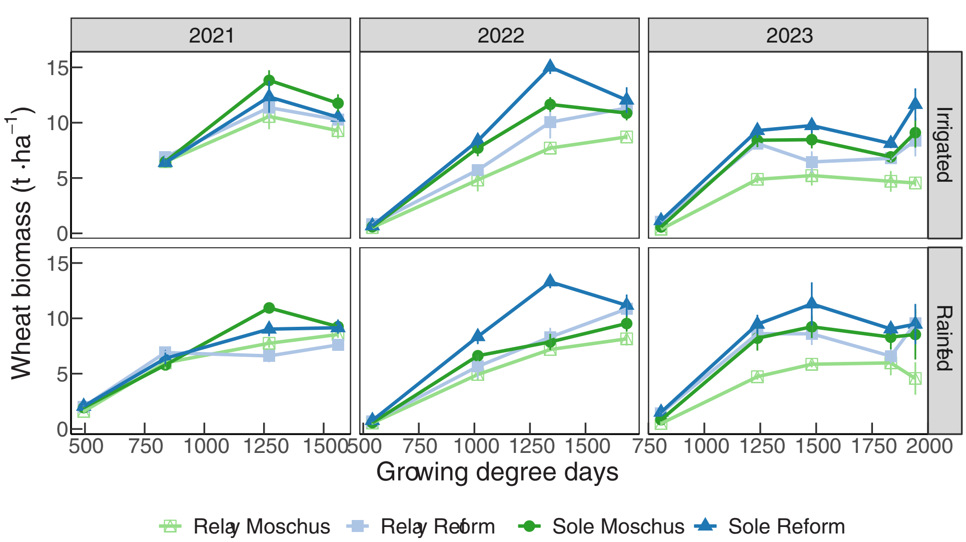

Fig. 4. Total wheat dry matter biomass (including ears) development over the growing season. Bars show SE. Growing degree days are calculated as days since sowing.

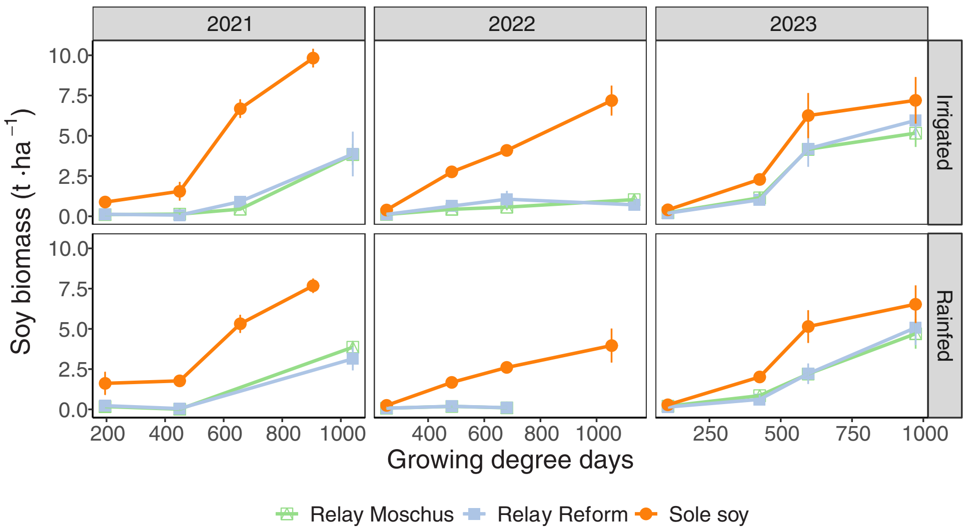

Fig. 5. Total soy biomass (including pods) development over the growing season. Bars show SE. Growing degree days are calculated as days since sowing.

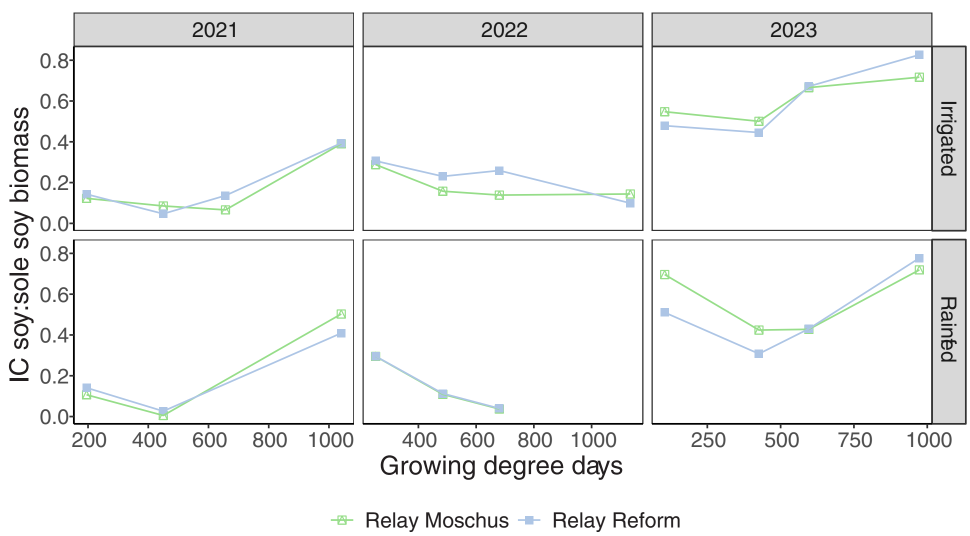

Fig. 6. The recovery reponse of soy after wheat harvestshown by the monthly average of ratio of intercropped soy biomass:sole soy biomass. A ratio of 1 would indicate that the intercropped soy fully reached the biomass of the sole soy. Growing degree days are calculated as days since sowing.

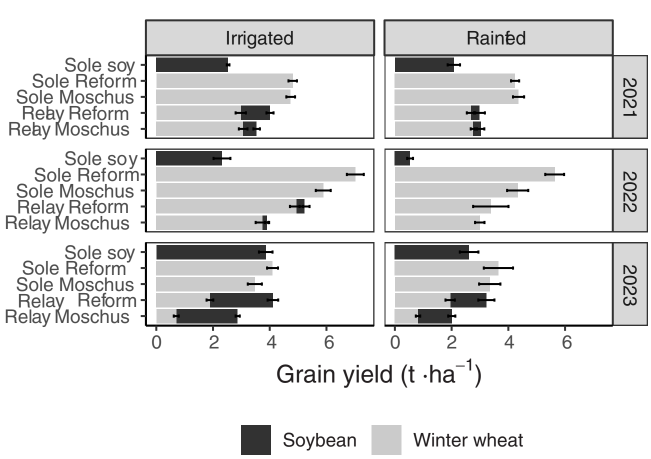

Fig. 7. Total grain yields per treatment. Error bars represent SE.

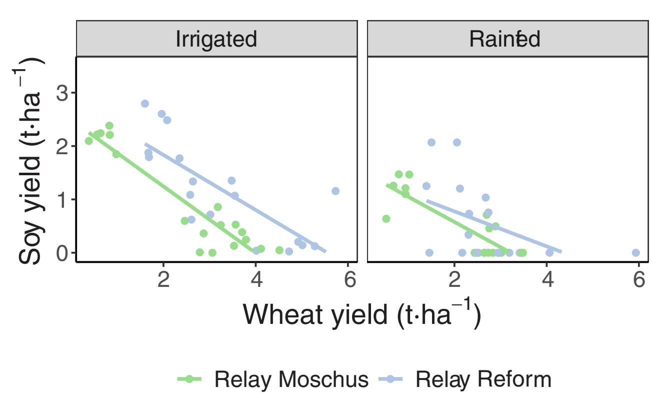

Fig. 8. Relationship between crop yields in the relay system. Points represent individual plots.

as there was a significant negative correlation between the two (Fig. 8) for both irrigated (Moschus r = -0.93, $p < 0.001$; Reform r = -0.078, p = 0.0001) and rainfed treatments (Moschus r = -0.85, $p < 0.0001$; Reform r = 0.49, p = 0.046). Soy generally had very low yields (<0.2 tons·ha^{-1}) once wheat yielded over 4 tons·ha^{-1}. The LERs of all cropping treatments ranged from 0.60 to 1.02 with rainfed treatments having a lower average LER (0.77; Table 2) than irrigated treatments (0.86) and Moschus systems having a lower LER (0.75) than Reform based systems (0.88). The TOI for all systems varied from 0.60 to 1.00.

We found no effect of irrigation on wheat protein content (Supplemental Materials). Moschus generally had higher protein content than Reform in 2022 ($p < 0.001$) and 2023 ($p < 0.001$). As for soy, irrigated Reform relay soy (38.9 %) had significantly higher protein content than irrigated sole soy (32.1 %, p = 0.049) in 2021 but there were no other differences in soy protein content in other years.

4. Discussion

Our results indicate that relay intercropping with soy and winter wheat is not a viable crop diversification strategy under water limiting conditions. Relay soy yields were extremely low or nonexistent in two (2021 and 2022) out of three years, making the system an economic failure. In 2023, when relay soy yields were relatively high, the LER of the system barely reached 1 indicating that the relay system had a less efficient land use compared to sole cropping. Even with variations in management, including different wheat varieties and irrigation, relay intercropping was not able to outperform sole cropping. In other studies, relay intercropping of soy and winter cereals demonstrated LERs between 1.3 and 1.8 (Caviglia et al., 2011; Raza et al., 2023) while some showed significant yield reductions (Duncan and Schapaugh, 1997; Oltmanns, Becker, 2023; Świtek et al., 2024) or mixed results (Sanderman et al., 2017). Differences in climatic conditions such as higher precipitation (Caviglia et al., 2011) or arid irrigated conditions (Raza et al., 2023) may have helped to alleviate resource competition in other studies. Our results are consistent with other trials in central Europe that found strong decreases in soy yield or soy crop failure in similar experimental setups with winter cereals. Even with wider rows to alleviate competition, high soy yields were not achieved (Świtek et al., 2024), indicating a more fundamental problem with the system and crop choices in drier regions. However, most of the trials in Central Europe exist only as project reports rather than peer reviewed studies (Klaiss, pers.com; Oltmanns, Becker, 2023) showing the paucity of experimental data on the topic.

As seen by the strong negative relationships between wheat and soy yields, the crops likely competed for resources in the relay intercropping system. In 2021 and 2022, relay wheat yielded 65 % that of sole wheat and despite the 50 % reduction in wheat density compared to sole crops, we found that wheat biomass reached up to 97 % of sole wheat biomass. This overyielding indicates that wheat was not the relay partner suffering from resource competition but rather soy. In intercropping mixtures, wheat is often the dominant crop competing for resources (Liu et al., 2015; Mariotti et al., 2009; Wang et al., 2022) and is already established with a developed root system months before the soy cultivation. Across years, competition in the relay systems appeared to strongly affect soy outcomes. The rario of relay soy:sole soy biomass even decreased from June to July indicating stress during this critical time period. While recovering slightly after the wheat harvest, relay soy only reached 12 %-80 % (average 32 %) of the sole soy biomass by the end of the growing season despite being planted at the same density, which had strong implications for soy yield.

Table 2
Land equivalent ratios (LER) and transgressive overyielding indices (TOI) of each intercropping system based on grain yields.

		Rainfed		Irrigated	
Year	Variety	LER	TOI	LER	TOI
2021	Moschus	0.84	0.69	0.83	0.75
	Reform	0.77	0.7	1.02	0.83
2022	Moschus	0.69	0.69	0.72	0.66
	Reform	0.60	0.60	0.82	0.75
2023	Moschus	0.69	0.60	0.76	0.74
	Reform	1.02	0.89	1.03	1.00

4.1. Soil water competition in relay intercropping negatively affects soy yields

Irrigated crops yielded more than rainfed crops, especially intercropped soy which increased by 73 %-250 % with irrigation across the 3 experimental years. This suggests that soil water was, to a large extent, limiting soy growth in relay intercropping. Models estimate that despite an increased water use efficiency, water needs in relay intercropping of wheat and maize can be up to 54 % higher than sole crops (Tan et al., 2020) and empirical studies have shown that intercropping has higher water consumption (Caviglia et al., 2004; Ma et al., 2020). Increased water demand poses a problem in areas with low precipitation or soils with low water retention. The struggle of relay intercropping with low precipitation is consistent with other studies (Duncan and Schapaugh, 1997; Sandler et al., 2015) and it has been suggested that soy-winter wheat relay intercropping should not be used in drought prone areas or only with weak wheat stands (Duncan and Schapaugh, 1997).

Two of our three experimental years suffered from low precipitation and there was a strong water deficit (-280 and −470 mm in 2021 and 2022) by the end of the soy growing season. This water deficit may have affected the intercropped soy in different ways. In 2021, the deficit was strongest in June and July, during soy flowering. Soy is sensitive to water stress at this time, as yields are especially affected by water deficit during flowering to pod formation (Doss et al., 1974; Morrison et al., 2006). Relay soy biomass gains in this time were minimal, and the soy only began to grow again after wheat was harvested. However, despite the partial recovery of intercropped soy, soy yields were, averaged across irrigation treatments, only 29 % of sole soy with wheat variety Reform and 16 % with Moschus despite being planted at the same density, showing the lasting implications of competition during the co-growth phase.

In 2022, there was a significant water deficit of −160 mm at the time of soy drilling and the soil moisture content at this time was on average, less than 8 % which is below the permanent wilting point of our soil (Rab et al., 2011; Salter and Williams, 1965). In 2022, relay soy germinated but most plants died as seedlings, which is consistent with Sandler et al. (2015) who found that due to early season drought, many of the relayed crops died due to water competition with wheat. Early water stress in the seedbed has also been found to negatively affect soy seed germination and seedling emergence vigor, much more so in relay cropping than conventional cropping (Lamichhane et al., 2023). The warm and dry conditions throughout the rest of the growing season likely further exacerbated this initial deficit, leading to a very low soy plant count and reduced biomass of the surviving soy. In some cases, i.e. 2022 rainfed relay, 100 % of the soy plants died. Soy has a high water requirement for germination and establishment (Lamichhane et al., 2023) and legumes relay intercropped with wheat must meet water requirements during their co-growth stages for successful legume crop production (Vrignon-Brenas et al., 2016). The differing responses of soy to water deficits in 2021 and 2022 demonstrate the difficulty of relay intercropping where the resource needs of multiple crops must be managed simultaneously.

4.2. Light competition in relay intercropping

Relay intercropping systems can suffer from light competition as the established first crop can shade the growing second crop. In a soy wheat relay cropping trial, authors attributed part of the soy's failure to shading by wheat (Duncan and Schapaugh Jr., 1997). Our results align with (Caviglia et al., 2011) who found that soy relay intercropped with wheat received less PAR compared to sole or double cropped soy which led to lower yields. Shading by wheat likely affected soy growth in our trials, as relay soy received 21–88 % (average 54 %) of the PAR received by the sole soy canopy. Soy is most sensitive to shading by neighboring plants in the late vegetative stage as indicated by node branching and final grain yield (Mathew et al., 2000), when plants are in their co-growth stage in relay cropping. Nevertheless, light competition may not have been the main driver of poor soy growth and yield. While similar in many traits including ear emergence, maturity, and lodging, Moschus is a taller wheat variety than Reform (average 7 cm taller) and would hypothetically further reduce PAR available to the intercropped soy. However, we found no difference in soy yield between soy intercropped with Reform or Moschus in 2022 or 2023. Moreover, PAR availability is a function of soy height as taller soy can intercept more PAR under the wheat canopy, and the initial soy growth appeared to be very water limited in our study. This indicates that in our trial, selecting cereal varieties by height to manage light competition is likely not as important as selecting varieties with lower water needs or an early maturing variety that would reduce the co-growth stage. This is supported by Nelson et al. (2010) who found that when intercropped with cereals and grains, relay soy yields were significantly reduced by a more vigorous wheat variety compared to a lower-yielding one.

4.3. Future of relay intercropping and management implications

This study was a comprehensive, three-year trial with both agronomic and crop physiological data allowing insight into the performance of soy-winter wheat relay intercropping with the full dataset available online (see Data Availability). Narrow rows of soy and wheat are poor relay intercropping partners in drought prone regions without heavy irrigation, and significant management changes are likely needed for relay cropping to work. Even in trials in wetter regions (Klaiss, pers.com; Oltmanns, Becker, 2023) or with wider rows to alleviate crop competition (Świtek et al., 2024), soy yields were low or nonexistent. Future studies looking comprehensively into soil water dynamics between intercrops, especially at deeper soil depths, could be useful in understanding and mitigating competitive interactions.

While we found that irrigation increased intercropping yields, the increases in yield are likely not worth the additional cost to farmers. Irrigation also, based on our observations, increased weed cover in relay intercropping plots where the soy was smaller and provided less ground cover compared to sole crops. This could have further increased resource competition as the weeds grew much faster than the soy highlighting the difficulty of weed control in relay systems where approved herbicides are non-existent and physical cultivation is not always possible.

If growers are still interested in relay cropping, either the weaker partner needs the better resource conditions and should be planted first (e.g. a winter legume with a spring cereal) or a more drought tolerant second crop (e.g. chickpea) could be paired with a weaker partner (e.g. spring cereal). Finally, utilizing strip cropping of component crops, whether this be narrow row strip cropping (2–5 m) or wide row cropping (6–36 m), could help to nearly fully alleviate crop resource competition as there is little area where the crops interact. Albeit this method removes nearly all of the potential belowground interactions (and mixture benefits), the systems still introduce biodiversity into an otherwise sole cropped field which has benefits for non-crop biodiversity and pest control (Thompson et al., 2025).

5. Conclusion

This study was one of the first in Central Europe to test soy-winter wheat relay intercropping with various management strategies (irrigation and variety) and comprehensive measurements of biotic and abiotic processes in a three-year field trial. We found that the system managed with winter wheat and soy is unsuitable in drought prone conditions due to competition of water and subsequently light in the co-growth period which negatively affected soy establishment, growth, and yields. While the system has been found to be productive in other regions with potential environmental benefits, management changes are necessary for relay intercropping success in dry regions, especially with a competitive cereal and a legume in an intensive cropping system. Future trials should be focused on mitigating water competition, specifically with alternative component crops and possibly different varieties and arrangements conducive to reducing water stress.

Funding

This project was supported by the Leibniz Centre for Agricultural Landscape Research (ZALF) through the integrated priority project: Cropping system diversification to increase the resilience of farming systems (divCROP) 2021–2024.

CRediT authorship contribution statement

Moritz Reckling: Resources, Funding acquisition, Writing – review & editing, Methodology, Supervision, Conceptualization. **Jing Yu:** Investigation, Writing – review & editing, Methodology. **Sonoko D. Bellingrath-Kimura:** Methodology, Writing – review & editing. **Thomas F. Döring:** Methodology, Conceptualization, Writing – review & editing. **Thompson Jennifer B:** Visualization, Formal analysis, Writing – original draft, Investigation, Writing – review & editing, Methodology.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We would like to thank Christoph Müller, Julien Cadiran, and Kritika Chouhan for their support in the field as well as everyone in the working group Resource Efficient Cropping systems for their help. We would also like to thank the ZALF research station and central lab for their support.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fcr.2025.110083.

Data availability

The full dataset is available in the Bonares data depository: https://doi.org/10.4228/zalf-yw6r-ad61

References

Beillouin, D., Ben-Ari, T., Malézieux, E., Seufert, V., Makowski, D., 2021. Positive but variable effects of crop diversification on biodiversity and ecosystem services. Glob. Change Biol. 27 (19), 4697–4710. https://doi.org/10.1111/gcb.15747.

Bonke, V., Musshoff, O., 2020. Understanding German farmer's intention to adopt mixed cropping using the theory of planned behavior. Agron. Sustain. Dev. 40 (6), 48. https://doi.org/10.1007/s13593-020-00653-0.

Caviglia, O.P., Sadras, V.O., Andrade, F.H., 2004. Intensification of agriculture in the south-eastern Pampas: I. Capture and efficiency in the use of water and radiation in double-cropped wheat–soybean. Field Crops Res. 87 (2), 117–129. https://doi.org/10.1016/j.fcr.2003.10.002.

Caviglia, O.P., Sadras, V.O., Andrade, F.H., 2011. Yield and Quality of Wheat and Soybean in Sole- and Double-Cropping. Agron. J. 103 (4), 1081–1089. https://doi.org/10.2134/agronj2011.0019.

Chen, G., Kong, X., Gan, Y., Zhang, R., Feng, F., Yu, A., Zhao, C., Wan, S., Chai, Q., 2018. Enhancing the systems productivity and water use efficiency through coordinated soil water sharing and compensation in strip-intercropping. Sci. Rep. 8 (1), 10494. https://doi.org/10.1038/s41598-018-28612-6.

Chen, P., Zheng, B., Yang, H., Du, Q., Fu, Z., Luo, K., Li, Y., Lin, P., Peng, X., Pu, T., Wu, Y., Wang, X., Yong, T., Yang, W., 2024. Relay intercropping boosts soybean recovery growth and delays nodule senescence to achieve yield advantages. Agric. Ecosyst. Environ. 369, 109030. https://doi.org/10.1016/j.agee.2024.109030.

Cong, W.-F., Hoffland, E., Li, L., Six, J., Sun, J.-H., Bao, X.-G., Zhang, F.-S., Van Der Werf, W., 2015. Intercropping enhances soil carbon and nitrogen. Glob. Change Biol. 21 (4), 1715–1726. https://doi.org/10.1111/gcb.12738.

Doss, B.D., Pearson, R.W., Rogers, H.T., 1974. Effect of Soil Water Stress at Various Growth Stages on Soybean Yield1. Agron. J. 66 (2), 297–299. https://doi.org/10.2134/agronj1974.00021962006600020032x.

Duchene, O., Vian, J.-F., Celette, F., 2017. Intercropping with legume for agroecological cropping systems: Complementarity and facilitation processes and the importance of soil microorganisms. A review. Agric. Ecosyst. Environ. 240, 148–161. https://doi.org/10.1016/j.agee.2017.02.019.

Duncan, S.R., Schapaugh, W.T., 1997. Relay-Intercropped Soybean in Different Water Regimes, Planting Patterns, and Winter Wheat Cultivars. J. Prod. Agric. 10 (1), 123–129. https://doi.org/10.2134/jpa1997.0123.

FAOSTAT . (2024). Retrieved 21 November 2024, from ⟨https://www.fao.org/faostat/en/#data/QCL/visualize⟩.

Himanen, S.J., Mäkinen, H., Rimhanen, K., Savikko, R., 2016. Engaging Farmers in Climate Change Adaptation Planning: Assessing Intercropping as a Means to Support Farm Adaptive Capacity. Article 3. Agriculture 6 (3). https://doi.org/10.3390/agriculture6030034.

Homulle, Z., George, T.S., Karley, A.J., 2022. Root traits with team benefits: Understanding belowground interactions in intercropping systems. Plant Soil 471 (1–2), 1–26. https://doi.org/10.1007/s11104-021-05165-8.

Kuepper, B., Riemersma, M., 2019. IDH and IUCN NL. Eur. Soy Monit. Rep. 2019. ⟨https://www.idhsustainabletrade.com/publication/european-soy-monitor-report-2019/⟩.

Lamichhane, J.R., Varaillas, C., Debaeke, P., 2023. Seedling emergence and biomass production of soybean cultivars under wheat-soybean relay cropping. PLOS ONE 18 (11), e0293671. https://doi.org/10.1371/journal.pone.0293671.

Lamichhane, J.R., Alletto, L., Cong, W.-F., Dayoub, E., Maury, P., Plaza-Bonilla, D., Reckling, M., Saia, S., Soltani, E., Tison, G., Debaeke, P., 2023. Relay cropping for sustainable intensification of agriculture across temperate regions: Crop management challenges and future research priorities. Field Crops Res. 291, 108795. https://doi.org/10.1016/j.fcr.2022.108795.

Letourneau, D.K., Armbrecht, I., Rivera, B.S., Lerma, J.M., Carmona, E.J., Daza, M.C., Escobar, S., Galindo, V., Gutiérrez, C., López, S.D., Mejía, J.L., Rangel, A.M.A., Rangel, J.H., Rivera, L., Saavedra, C.A., Torres, A.M., Trujillo, A.R., 2011. Does plant diversity benefit agroecosystems? A synthetic review. Ecol. Appl. 21 (1), 9–21. https://doi.org/10.1890/09-2026.1.

Li, C., Stomph, T.-J., Makowski, D., Li, H., Zhang, C., Zhang, F., van der Werf, W., 2023. The productive performance of intercropping. Proc. Natl. Acad. Sci. 120 (2), e2201886120. https://doi.org/10.1073/pnas.2201886120.

Li, L., Sun, J., Zhang, F., Li, X., Yang, S., Rengel, Z., 2001. Wheat/maize or wheat/soybean strip intercropping I. Yield advantage and interspecific interactions on nutrients. Field Crops Res. 71, 123–137. https://doi.org/10.1016/S0378-4290(01)00156-3.

Li, L., Tilman, D., Lambers, H., Zhang, F.-S., 2014. Plant diversity and overyielding: Insights from belowground facilitation of intercropping in agriculture. N. Phytol. 203 (1), 63–69. https://doi.org/10.1111/nph.12778.

Li, Q.-Z., Sun, J.-H., Wei, X.-J., Christie, P., Zhang, F.-S., Li, L., 2011. Overyielding and interspecific interactions mediated by nitrogen fertilization in strip intercropping of maize with faba bean, wheat and barley. Plant Soil 339 (1), 147–161. https://doi.org/10.1007/s11104-010-0561-5.

Liu, Y.X., Zhang, W.P., Sun, J.H., Li, X.F., Christie, P., Li, L., 2015. High morphological and physiological plasticity of wheat roots is conducive to higher competitive ability of wheat than maize in intercropping systems. Plant Soil 397, 387–399.

Lopes, T., Hatt, S., Xu, Q., Chen, J., Liu, Y., Francis, F., 2016. Wheat (Triticum aestivum L.)-based intercropping systems for biological pest control. Pest Manag. Sci. 72 (12), 2193–2202. https://doi.org/10.1002/ps.4332.

Ma, L., Li, Y., Wu, P., Zhao, X., Chen, X., Gao, X., 2020. Coupling evapotranspiration partitioning with water migration to identify the water consumption characteristics of wheat and maize in an intercropping system. Agric. For. Meteorol. 290, 108034. https://doi.org/10.1016/j.agrformet.2020.108034.

Mamine, F., Farès, M., 2020. Barriers and Levers to Developing Wheat–Pea Intercropping in Europe: A Review. Article 17. Sustainability 12 (17). https://doi.org/10.3390/su12176962.

Mariotti, F., Tomé, D., Mirand, P.P., 2008. Converting Nitrogen into Protein—Beyond 6.25 and Jones' Factors. Crit. Rev. Food Sci. Nutr. 48 (2), 177–184. https://doi.org/10.1080/10408390701279749.

Mariotti, M., Masoni, A., Ercoli, L., Arduini, I., 2009. Above- and below-ground competition between barley, wheat, lupin and vetch in a cereal and legume intercropping system. Grass Forage Sci. 64, 401–412.

Mathew, J.P., Herbert, S.J., Zhang, S., Rautenkranz, A.A.F., Litchfield, G.V., 2000. Differential Response of Soybean Yield Components to the Timing of Light Enrichment. Agron. J. 92 (6), 1156–1161. https://doi.org/10.2134/agronj2000.9261156x.

Morrison, M.J., McLaughlin, N.B., Cober, E.R., Butler, G.M., 2006. When is short-season soybean most susceptible to water stress? (Special Issue). Can. J. Plant Sci. 86, 1327–1331. https://doi.org/10.4141/P06-115.

Nelson, K.A., Meinhardt, C.G., Smoot, R.L., 2010. Wheat (Triticum aestivum L.) cultivar selection affects double-crop and relay-intercrop soybean (Glycine max L.) response on claypan soils. Int. J. Agron. 2010 (1), 543261.

Oltmanns, M., Becker, K., 2023. Soja on top – Anbau von Weizen und Soja in Mischkultur. bis 10. März 2023. In: One Step Ahead - einen Schritt voraus! Beiträge zur 16. Wissenschaftstagung Ökologischer Landbau, Frick (CH), 7. Verlag Dr, Köster, Berlin.

R Core Team (2024). R: A Language and Environment for Statistical Computing_. R Foundation for Statistical Computing, Vienna, Austria. <⟨https://www.R-project.org/⟩>.

Rab, M.A., Chandra, S., Fisher, P.D., Robinson, N.J., Kitching, M., Aumann, C.D., Imhof, M., 2011. Modelling and prediction of soil water contents at field capacity and permanent wilting point of dryland cropping soils. Soil Res. 49 (5), 389–407.

Raza, M.A., Din, A.M.U., Zhiqi, W., Gul, H., Ur Rehman, S., Bukhari, B., Haider, I., Rahman, M.H.U., Liang, X., Luo, S., El Sabagh, A., Qin, R., Zhongming, M., 2023. Spatial differences influence nitrogen uptake, grain yield, and land-use advantage of wheat/soybean relay intercropping systems. Article 1 Sci. Rep. 13 (1). https://doi.org/10.1038/s41598-023-43288-3.

Salter, P.J., Williams, J.B., 1965. The Influence of Texture on the Moisture Characteristics of Soils. J. Soil Sci. 16 (2), 310–317. https://doi.org/10.1111/j.1365-2389.1965.tb01442.x.

Sanderman, J., Hengl, T., Fiske, G.J., 2017. Soil carbon debt of 12,000 years of human land use. Proc. Natl. Acad. Sci. 114 (36), 9575–9580. https://doi.org/10.1073/pnas.1706103114.

Sandler, L., Nelson, K.A., Dudenhoeffer, C., 2015. Winter Wheat Row Spacing and Alternative Crop Effects on Relay-Intercrop, Double-Crop, and Wheat Yields. Int. J. Agron. 2015 (1), 369243. https://doi.org/10.1155/2015/369243.

Simon-Miquel, G., Reckling, M., Lampurlanés, J., Plaza-Bonilla, D., 2023. A win-win situation – Increasing protein production and reducing synthetic N fertilizer use by integrating soybean into irrigated Mediterranean cropping systems. Eur. J. Agron. 146, 126817. https://doi.org/10.1016/j.eja.2023.126817.

Sun, B., Gao, Y., Yang, H., Zhang, W., Li, Z., 2019. Performance of alfalfa rather than maize stimulates system phosphorus uptake and overyielding of maize/alfalfa intercropping via changes in soil water balance and root morphology and distribution in a light chernozemic soil. Plant Soil 439 (1), 145–161. https://doi.org/10.1007/s11104-018-3888-y.

Świtek, S., Majchrzycki, W., Taras, A., Piechota, T., 2024. Relay Intercropping of Soybean and Winter Barley in Polish Climatic Conditions—Importance of Strip Width and Yearly Weather. Article 11. Agronomy 14 (11). https://doi.org/10.3390/agronomy14112736.

Tan, M., Gou, F., Stomph, T.J., Wang, J., Yin, W., Zhang, L., Chai, Q., van der Werf, W., 2020. Dynamic process-based modelling of crop growth and competitive water extraction in relay strip intercropping: Model development and application to wheat-maize intercropping. Field Crops Res. 246, 107613. https://doi.org/10.1016/j.fcr.2019.107613.

Thompson, J.B., Döring, T.F., Bellingrath-Kimura, S.D., Grahmann, K., Glemnitz, M., Reckling, M., 2025. Spatial arrangement of intercropping impacts natural enemy abundance and aphid predation in an intensive farming system. Agric. Ecosyst. Environ. 378, 109324. https://doi.org/10.1016/j.agee.2024.109324.

Vrignon-Brenas, S., Celette, F., Piquet-Pissaloux, A., David, C., 2016. Biotic and abiotic factors impacting establishment and growth of relay intercropped forage legumes. Eur. J. Agron. 81, 169–177. https://doi.org/10.1016/j.eja.2016.09.018.

Wallace, S.U., Bacanamwo, M., Palmer, J.H., Hull, S.A., 1996. Yield and yield components of relay-intercropped wheat and soybean. Field Crops Res. 46 (1), 161–168. https://doi.org/10.1016/0378-4290(95)00009-7.

Wang, W., Li, M.-Y., Gong, D.-S., Zhou, R., Khan, A., Zhu, Y., Zhu, H., Abrar, M., Zhu, S.-G., Wang, B.-Z., Song, C., Xiong, Y.-C., 2022. Water use of intercropped species: Maize-soybean, soybean-wheat and wheat-maize. Agric. Water Manag. 269, 107690. https://doi.org/10.1016/j.agwat.2022.107690.

Yang, F., Wang, X., Liao, D., Lu, F., Gao, R., Liu, W., Yong, T., Wu, X., Du, J., Liu, J., Yang, W., 2015. Yield Response to Different Planting Geometries in Maize-Soybean Relay Strip Intercropping Systems. Agron. J. 107 (1), 296–304. https://doi.org/10.2134/agronj14.0263.

Yang, F., Liao, D., Wu, X., Gao, R., Fan, Y., Raza, M.A., Wang, X., Yong, T., Liu, W., Liu, J., Du, J., Shu, K., Yang, W., 2017. Effect of aboveground and belowground interactions on the intercrop yields in maize-soybean relay intercropping systems. Field Crops Res. 203, 16–23. https://doi.org/10.1016/j.fcr.2016.12.007.

Zhang, F., Li, L., 2003. Using competitive and facilitative interactions in intercropping systems enhances crop productivity and nutrient-use efficiency. Plant Soil 248, 305–312.

Zhang, Y., Sun, Z., Su, Z., Du, G., Bai, W., Wang, Q., Wang, R., Nie, J., Sun, T., Feng, C., Zhang, Z., Yang, N., Zhang, X., Evers, J.B., van der Werf, W., Zhang, L., 2022. Root plasticity and interspecific complementarity improve yields and water use efficiency of maize/soybean intercropping in a water-limited condition. Field Crops Res. 282, 108523. https://doi.org/10.1016/j.fcr.2022.108523.