



# Positive effects of intercrop yields in farms from across Europe depend on rainfall, crop composition, and management

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## Abstract

Modern “intensive” agriculture drives the biodiversity-climate crisis but is also central to global food security. Future farming needs management approaches that maintain (or even enhance) food production while reducing negative climate and biodiversity impacts. Intercrops could provide part of the solution, increasing biodiversity and boosting production with fewer inputs. However, barriers remain to their wide-scale uptake, in particular tailoring intercrops to local equipment, management practice, and environment. We analyze data from multiple trials of cereal-legume intercrops conducted on farms across Europe between 2018 and 2021. Our study is the first attempt, to our knowledge, to quantify the yield benefits of cereal-legume intercropping undertaken at commercially relevant scales for farms across Europe. We used crop performance ratio (CPR)—the ratio of the observed intercrop yield compared to the expected yield based on monoculture yields—as our metric of intercrop performance. Using CPR, we found a roughly 30% yield gain across all sites. However, CPR was modulated by a number of factors. CPR was not strongly affected by management except for the negative effects of direct drilling and the positive effects of organic fertilizer addition. CPR also depended on intercrop composition (number and identity of components), background yields (being highest where yields were lower), and rainfall (being higher with higher rainfall). Our findings allow us to reduce uncertainty about how intercrops will perform in realistic local farm conditions, give guidance for tailoring intercrops to local farming conditions, and provide key goals for further work to integrate intercrops into sustainable farming systems.

**Keywords** Agricultural management · Biodiversity · Climate · Intercropping and crop mixtures · Sustainable farming

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## 1 Introduction

The way we currently produce food and other agricultural products is under threat from a range of factors. It has also contributed to some of these threats, including the changing climate, depleted biodiversity, and declining availability of natural resources used to boost productivity (Steffen et al. 2015; IPES Food 2016; Gladek et al. 2017). Agriculture is a producer of greenhouse gas (GHG) emissions (IPCC 2020), primarily from fertilizer use, and agriculture has been a major driver of biodiversity loss (Jaureguiberry et al. 2022; Bicknell et al. 2023) through mechanization, habitat degradation, and widespread pesticide use (Robinson and Sutherland 2002; Critchley et al. 2006; Storkey et al. 2012). Future farming systems need to co-deliver for nature and net zero without compromising global food security, which is already vulnerable to external shocks, as highlighted by the Covid-19 pandemic (Laborde et al. 2020), and more recently the war in Ukraine (Ben Hassen and El Bilali 2022), which affected fertilizer costs, food supplies, and food prices (Benton et al. 2022).

The need for food system transformation has been widely recognized (IPES Food 2016), but transformational change takes years or decades (Barrett et al. 2020). What can farmers do now to address these multiple challenges? Intercropping—where two or more crop species are grown simultaneously on the same piece of land (Vandermeer 1989)—could provide one solution. There are many ways in which intercropping can be practiced, as summarized in Brooker et al. (2015) and Homulle et al. (2022). These range from mixtures harvested together (Fig. 1) for use as mixed-grain “whole crops” or for separation post-harvest to relay intercrops grown together but harvested on separate dates, through to unharvested companion crops supporting the growth of a cash crop.

Importantly, intercropping offers a relatively simple way of delivering benefits from enhancing biodiversity at the within-field level. Observed benefits from intercropping include reduced yield variability (López-Angulo et al. 2023), decreased weed competition (Gu et al. 2021), and durable disease control (Zhang et al. 2019; Newton and Guy 2009), enabling reduced inputs and greenhouse gas emissions (Brooker et al. 2015, 2021; Yu et al. 2016; Zhang et al. 2019). The underpinning mechanisms have been reviewed comprehensively (e.g., Bedoussac et al. 2015; Brooker et al. 2015; Homulle et al. 2022; Engbersen et al. 2022), and collectively, these outcomes have the potential to improve food security (Kiær et al. 2012; Martin-Guay et al. 2018; Li et al. 2020a), increase carbon sequestration (Cong et al. 2014), and enhance agrobiodiversity (Brooker et al. 2016; Brandmeier et al. 2021).



**Fig. 1** Intercrop trial at James Hutton Institute Balruddery Farm, Scotland, May 2018. The trial is a mixture of barley and peas. The image shows the close spatial association of the components within the crop mixture, which was sown in a single pass following pre-mixing of the peas and barley seed.

While intercrops can bring benefits across a wide range of ecosystem services (Brooker et al. 2021), impacts on yield are a key part of the evidence base. The land equivalent ratio (LER; Willey 1979) is commonly used to assess intercrop performance, and is the ratio of the land area under sole cropping to the area needed to produce the same yield with the same management level under intercropping. LER values greater than one indicate that intercrops yield more per unit area than the component monocrops (Willey 1979; Harris et al. 1987). Meta-analyses show yield benefits from intercropping, including a median LER of 1.17 (Yu et al. 2016) and an average LER of 1.3 (Martin-Guay et al. 2018). However, although yield gains and other benefits of intercrops are

well established, and some of the mechanisms that underpin them are relatively well characterized, crop mixtures are still not widely adopted in modern farming (Brooker et al. 2016). Barriers to the wide-scale uptake of crop mixtures range from on-farm technical know-how and access to appropriate equipment to market acceptability, regulation, and incentivization (Bedoussac et al. 2015; Tippin et al. 2019; Morel et al. 2020; Brannan et al. 2023). In terms of providing technical information for farmers, it is important to answer the question “how will it work on my farm, and with my management regime and equipment”? As part of the process of overcoming barriers to uptake, it is important for farmers to know whether they will see the benefits of intercropping.

Like any farming practice, intercrop performance is context dependent (Weih et al. 2021), but ecological theory provides frameworks for understanding this context dependency. In particular, the stress gradient hypothesis (SGH) (Bertness and Callaway 1994; Brooker et al. 2008) indicates that positive plant-plant interactions which underpin some of the benefits of intercropping might be enhanced under more severe environmental conditions, for example under reduced fertilizer inputs or water-limited conditions. In addition, it is well established for many natural and semi-natural habitats that increasing biodiversity has positive effects on productivity, stability, and nature-based ecosystem service delivery (Cardinale et al. 2012; Soliveres et al. 2016; Wan et al. 2022). Intercrops provide a means to rapidly increase plant diversity within an agricultural field, and because plant diversity is being elevated in a very low-diversity system—at the extremely low end of the Biodiversity-Ecosystem Function (BEF) spectrum—the potential for positive outcomes for agroecosystem function is large.

Overall, therefore, to provide reassurance to farmers about the likely benefits of intercropping for their farm regime, equipment, and location, we need to know which factors regulate the success of intercrops at local and regional scales so that crop mixtures and their associated management can be tailored to specific locations and situations (Gardarin et al. 2022). However, much of the supporting evidence for intercropping benefits comes from experiments on individual research farms with highly controlled designs and replicated treatments. These trials are extremely helpful in developing the evidence base and understanding of fundamental processes regulating intercrop performance. But important evidence gaps remain concerning the success of intercrops in commercial settings where environmental conditions and agronomic practices vary between farms, regions, and countries, particularly whether intercrop benefits respond to management practice, or in a manner that we predict from fundamental ecological theories such as the SGH and BEF relationships. Evidence is needed as to whether the scale of benefit found in meta-analyses holds true for common on-farm conditions, as well as to help us understand (and

so provide advice concerning) the effects of in-field management (exploring whether the benefits from intercropping vary with management approach and crop diversity) and the impacts of large-scale environmental drivers such as climate.

Here, we address these issues by analyzing data from multiple trials of mainly cereal-legume intercrops conducted on farms across Europe between 2018 and 2021 as part of the DIVERSify and SEAMS projects ([www.plant-teams.org](http://www.plant-teams.org); <https://www.hutton.ac.uk/research/projects/seams-sustainability-education-and-agriculture-using-mixtures>; accessed 31 March 2024). All trials were carried out in arable cropping systems and in a coordinated way with standardized protocols for collecting data. The substantial majority of field sites (19 out of 22) were commercial farms, the other three being on research farms which were included to maximize the number of trials in this study while as far as possible mimicking commercial farm implementation in terms of large plot sizes and standard farming equipment. This provides an unparalleled opportunity to apply meta-analysis to a dataset much of which was collected in realistic farm settings, and unlike any already available from the published literature. Using this dataset, we tested the effects of crop management (crop composition, soil cultivation, agrochemical inputs) and key climate variables (temperature, rainfall), both independently and in combination, on intercrop yields. Our expectation—based on the SGH—was that the yield benefits of intercropping would be higher under more severe environmental conditions.

## 2 Materials and methods

### 2.1 Experimental data

Field trials of cereal-legume and legume-legume intercrops were conducted on 19 commercial farms and three research farms in four European countries covering northern (UK, Denmark), central (Austria), and southern (Italy) European regions (see Fig. 2). Each of the 172 trials lasted for a single year, with all trials conducted during the period 2018 to 2021. Each trial included a minimum of three treatments, comprising the intercrop and each intercrop component in monoculture. Plot sizes ranged from <1 to >5 ha. Except for the research farm trials, there was no replication of treatments within a trial; hence, each trial represented a single replicate in the meta-analysis, with the research farm trials included in the analysis by using the mean values of each treatment. The trials varied in their design, management treatments, and crop combinations tested. Data were collected from the researchers or farmers running the trials, with information collected or provided by farmers on a standardized set of parameters including management and yield. The metadata and data collected from the trials (described in Banfield-Zanin et al. 2017) were entered into

**Fig. 2** Map showing distribution of trial sites across Europe.



standardized templates for data collation and included sowing and harvest dates and final yield (grain or biomass) of each treatment. The combinations of cereals and legumes tested are shown in Supplementary Material.

## 2.2 Choice of metric

Although widely used to assess the production benefits of intercropping (Khanal et al. 2021), LER was not seen as a suitable metric for our purposes for three reasons: (1) it does not take into account the potential of farmers to vary the ratio of the species used in the intercrop; (2) to calculate LER, the components of the intercrop have to be separated, and technology or labor for undertaking separation was not available in all circumstances; and (3) LER measures how much extra land is needed, whereas many farmers have a fixed area of land such

that a metric expressing yield gain from the intercrop is more directly relevant.

With the above in mind, we selected the crop performance ratio (CPR, Harris et al. 1987), equivalent to the net effect ratio, as used, for example, by Li et al. (2023). CPR is the ratio of the observed intercrop yield compared to the expected yield based on monoculture yields, and values greater than one indicate that intercrops yield more per unit area than the component monocrops. CPR is the most suitable metric for our purposes, as (1) it allows for the ratio of components to vary, (2) it does not need separation of the intercrop, and (3) it measures the yield gain for a fixed area. When considering two intercropped species, CPR is expressed as:

$$CPR = \frac{Y1_c + Y2_c}{Z1_c Y1_m + Z2_c Y2_m}$$

where  $Y1_c$  and  $Y2_c$  are the yields of crops 1 and 2 when grown together,  $Z1_c$  and  $Z2_c$  are the proportions of crops 1 and 2 in the intercrop based on sowing rate (commonly  $\text{kg ha}^{-1}$ , and for each component is expressed as a proportion of the total sowing rate of the mixed crop), and  $Y1_m$  and  $Y2_m$  are the yields of the two crops when grown separately as monocultures. Following Oyejola and Mead (1982), means of the monocultures and intercrops across each trial were used in calculating CPR.

### 2.3 Weather data

Weather data for the growing season of each trial was sourced from the E-OBS ENSEMBLES daily gridded observational dataset for rainfall, temperature, and sea level pressure in Europe (Cornes et al. 2018). Data for daily maximum, mean, and minimum temperatures, as well as daily rainfall, at a resolution of  $0.1^\circ$  (c. 11.1 km latitude) were used to calculate the following growing season indices for each trial: mean temperature ( $^\circ\text{C}$ ), growing degree days ( $< 5^\circ\text{C}$ ), mean daily maximum temperature, highest maximum temperature, mean minimum temperature, lowest minimum temperature, mean daily rainfall (mm), and total rainfall.

### 2.4 Statistical analysis

All analyses were carried out in R version 4.1.2 (R Core Team 2021) using linear mixed models from the lme4 package (Bates et al. 2015) with probability testing from lmerTest (Kuznetsova et al. 2017) and predicted means calculated in emmeans (Lenth 2022). The random term in all models was Site, as multiple trials were run at some sites. Our dataset lacked the power to explore the interactive effect of key factors of interest in a single model and so, after assessing the mean effect of intercropping in a model with no fixed effect, separate categorical fixed models were tested for effects of the number of crops in the mixture (2 or 3); cereal type (Barley, Maize, None, Oats, Wheat); legume type (Beans, Beans + Vetch, Lentil, Lupin, Pea, Pea + Lupin, Vetch); fertilizer type (Inorganic nitrogen, None, Organic nitrogen); herbicide use (Herbicide, None); organic management (Conventional, Organic); tillage ([Direct] Drill, Minimum Tillage, Plough, Strip Tillage); note that capital letters on species names are used to denote model factors. To check whether any factors were confounded with one another, we produced correspondence tables (see Supplementary Material) showing the distribution of trials between different levels of different factors. Where there was a possibility that two or more factors were confounded, we note this in the results. The influence of weather variables was tested in separate models as continuous data, as was the relationship between monoculture yields and CPR. Very few trials (seven) used an oilseed, so this was not tested separately.

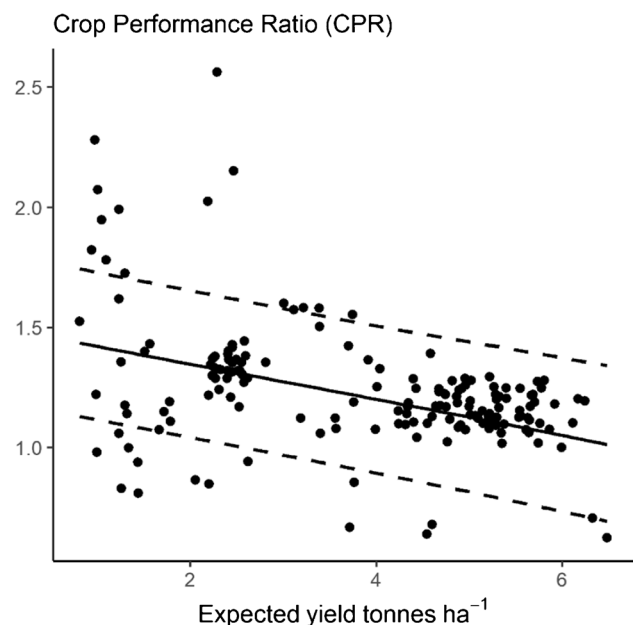
## 3 Results and discussion

### 3.1 Overall effect of intercropping

The overall mean CPR across all trials and sites was 1.28 (95% C.I. 1.15 and 1.40). Of the 172 trials in the dataset, only 14 had a CPR  $< 1.0$  (8.1%), indicating that the average CPR value is not driven by a small number of high-yielding intercrops. The yield benefits of intercropping, as measured by CPR, were highest at the lower end of the range of monoculture performance ( $df = 51.7$ ,  $t = 3.09$ ,  $p = 0.003$ , Fig. 3).

These yield gains are in agreement with findings from previous meta-analyses using data from the published literature which show on average positive yield benefits from intercrops (Yu et al. 2016; Martin-Guay et al. 2018; Li et al. 2020a). The average crop performance ratio (CPR) value of 1.28 indicates an approximate 30% yield gain, which is strikingly similar to the average net effect ratio value of 1.28 observed by Li et al. (2023). It is also similar to the average LER value found by Martin-Guay et al. (2018), although, as pointed out—for example, by Li et al. (2023)—these metrics are not directly comparable.

The yield benefits of intercropping appear greatest where yields are lowest, although CPR values were also more variable at low yields, and there was a greater chance of CPR values falling below 1 when the yield was less than 2 tonnes  $\text{ha}^{-1}$  (Fig. 3). This suggests that where monocrop yields are



**Fig. 3** Fitted relationship from the mixed effect model of CPR and the expected yield (tonnes  $\text{ha}^{-1}$ ) of the monocrops if grown in the proportion used in the mixture. Dashed lines indicate the 95% confidence intervals of the relationship.

high, the relative effect of beneficial interactions between two or more crops grown together is reduced, though CPR values still remain above 1. This matches expectations based upon the SGH that the benefits of intercrops are greater where environmental conditions are more severe. The trials in our database correspond to the low input “alternative production syndrome” of intercrop production (Li et al. 2020b) and in the absence of large fertilizer inputs we might expect intercrop benefits to be driven by niche differentiation (leading to enhanced resource use efficiency) and facilitation (Brooker et al. 2021).

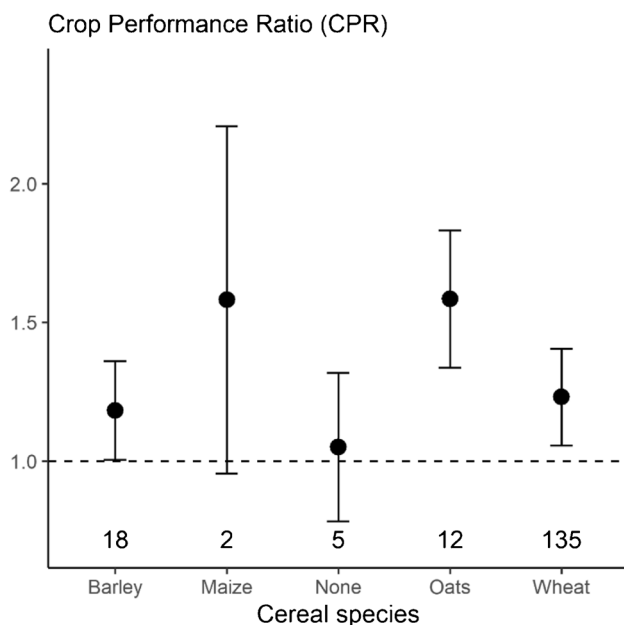
### 3.2 Effects of intercrop composition

There was a marginal, positive effect of increasing the number of species in the intercrop from 2 to 3; the predicted mean CPR of two species mixtures was 1.25, whereas the mean CPR of three species mixtures was 1.32 ( $df = 163.7$ ,  $t = 1.78$ ,  $p = 0.076$ ). There were differences in CPR associated with different cereal species (Fig. 4,  $df = 4$ ,  $37.4$ ,  $F = 3.78$ ,  $p = 0.011$ ) with an increase in the CPR value for mixtures containing Oats compared to Barley ( $df = 105.8$ ,  $t = 3.38$ ,  $p < 0.001$ ).

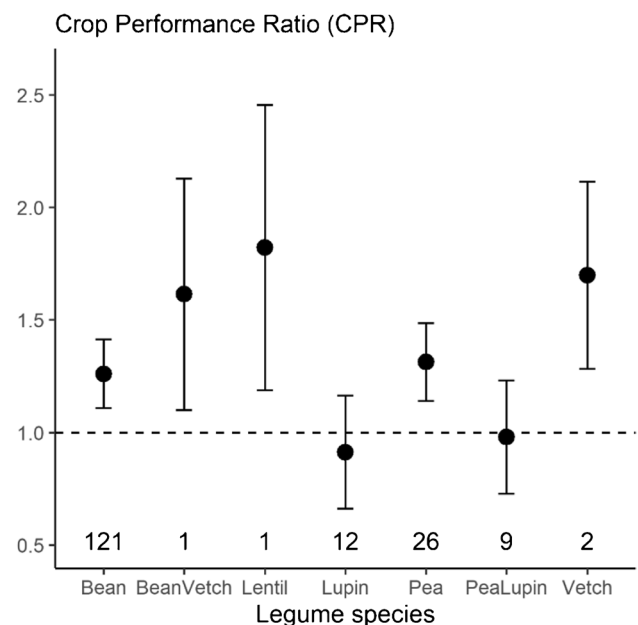
The effect of intercrop composition on CPR, both in terms of the number of crop components and their identity, is a second novel finding from our analyses. Improved

function (yield) with increasing component number affirms the assumption that intercropping shifts crop systems up the BEF curve, as has been shown previously for cultivar mixtures (Newton et al. 1997; Kiær et al. 2012). The effect of crop species identity on CPR values, particularly the positive effect of Oats, gives an exciting insight into the traits that might be driving facilitative interactions and niche differentiation mechanisms. For example, Oats can suppress soil-borne pathogens (Williams-Woodward et al. 1997; van Elsas et al. 2002) and have also been shown to promote legume nitrogen fixation (Tsialtas et al. 2018) and micronutrient accumulation (Zuo and Zhang 2008), presumably mediated by root exudates (Homulle et al. 2022). However, it is important to note that the majority of trials with Oats also used Organic nitrogen (Supplementary Material Table 2), which itself was associated with high CPR values (see below). There is clearly both a need and an opportunity for future studies to unpick the net positive effect of Oats independent of fertilizer treatment and understand the underlying mechanisms.

There were also differences in CPR between legume species (Fig. 5,  $df = 6$ ,  $81.8$ ,  $F = 4.17$ ,  $p = 0.001$ ). Mixtures containing Beans showed higher CPR values than those containing Lupin ( $df = 54.6$ ,  $t = 2.58$ ,  $p = 0.013$ ) or Peas and Lupin ( $df = 80.1$ ,  $t = 2.06$ ,  $p = 0.043$ ), and higher CPR values were produced by mixtures containing Vetch ( $df =$



**Fig. 4** Predicted mean CPR from the mixed model analysis for mixtures grown with different cereal species. Points show mean values for each category, with associated standard errors obtained from the linear mixed model calculated with emmeans (see Section 2). Values above the x-axis indicate the number of trials within each category, and the horizontal dashed line represents CPR = 1.



**Fig. 5** Predicted mean CPR from the mixed model analysis for mixtures grown with different legume species or mixes of legume species. Points show mean values for each category, with associated standard errors obtained from the linear mixed model calculated with emmeans (see Section 2). Values above the x-axis indicate the number of trials within each category, and the horizontal dashed line represents CPR = 1.

159,  $t = 2.18$ ,  $p = 0.031$ ) compared to those with Beans, Lupin, and Peas plus Lupin. However, only two trials contained Vetch, compared with 12 that contained Lupin (Supplementary Material Table 3), so the increase in CPR seen with Vetch should be interpreted with caution given this low sample size. There was no difference in CPR values between mixtures containing either of the two most popular legumes, Beans ( $n = 121$ ) and Pea ( $n = 26$ ,  $df = 46.7$ ,  $t = 0.54$ ,  $p = 0.595$ ). It is important to note that the majority of trials including Beans also included Wheat (Supplementary Material Table 1), so there may be a confounding effect of high yield from a particular cereal in the results for Beans, although this would not be the case for Peas. As for the species-specific effects of cereals, further work is needed to understand how above- or below-ground legume trait variation regulates CPR and how these trait-driven effects interact with site-specific conditions of resource availability and other environmental factors. However, they also show that commonly used legumes (peas and beans) work well as components of intercrops, making them a practical option as part of a mixed crop.

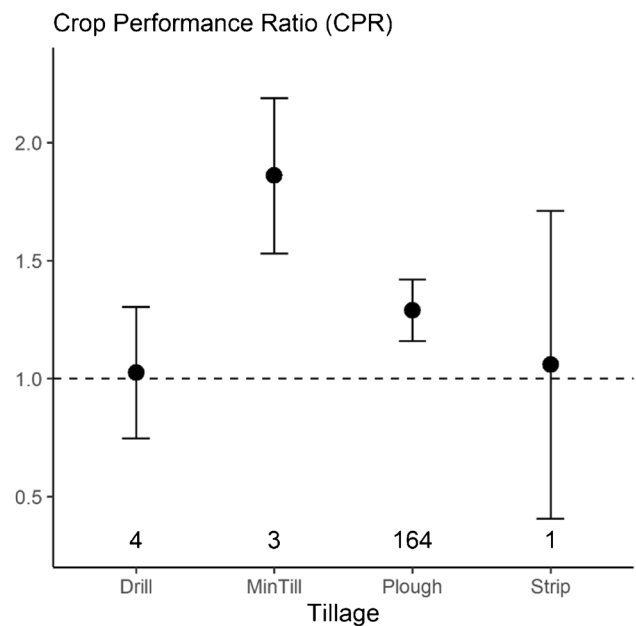
### 3.3 Effects of crop management

Management, as well as crop composition, modulated (CPR-assessed) yield gains delivered by intercrops. Tillage had an effect on CPR values (Fig. 6,  $df = 3$ ,  $75.3$ ,  $F = 5.90$ ,  $p = 0.001$ ), with CPR being lower under direct drilling than minimum tillage ( $df = 168$ ,  $t = 4.05$ ,  $p < 0.001$ ) and ploughed ( $df = 159$ ,  $t = 1.95$ ,  $p = 0.053$ ) fields. However, there were only three trials that employed minimum tillage, and all of these used organic nitrogen (Supplementary Material Table 4), so again, these results should be interpreted cautiously and taken as a focus for further study.

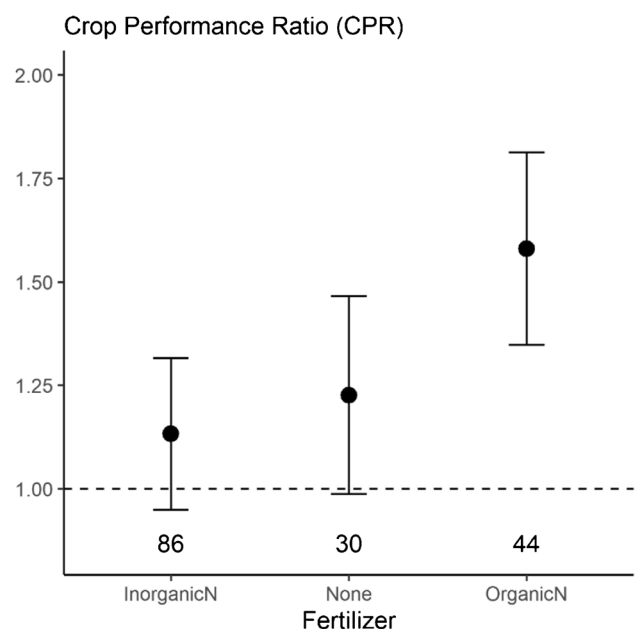
The variable effects of soil cultivation might result from the differential effects of soil surface disturbance and seed drill type on legume germination compared with cereals, as poor pea establishment has been noted in pea-barley intercrops when disk drilling through straw residue (AC Newton pers. comm.). These findings indicate that further work is needed to confirm whether minimum tillage is more suitable for sowing large-seeded species such as legumes, especially when intercropped with cereals that are less responsive to drilling and cultivation methods (Newton et al. 2021).

There were also significant impacts on CPR of fertilizer inputs (Fig. 7,  $df = 2$ ,  $23.1$ ,  $F = 7.65$ ,  $p = 0.003$ ), with trials using Organic nitrogen sources having a much higher CPR than trials using Inorganic nitrogen ( $df = 52.8$ ,  $t = 3.88$ ,  $p < 0.001$ ).

There was no effect of herbicide use on CPR values ( $df = 1$ ,  $25.8$ ,  $F = 0.72$ ,  $p = 0.405$ ), or of production practice (i.e., organic agriculture (44 trials reported) compared to conventional (160 trials reported);  $df = 1$ ,  $15.0$ ,  $F = 1.31$ ,  $p = 0.270$ ). The lack of herbicide effect might indicate that



**Fig. 6** Predicted mean CPR from the mixed model analysis for mixtures grown under different tillage methods. Points show mean values for each category, with associated standard errors obtained from the linear mixed model calculated with emmeans (see Section 2). Values above the x-axis indicate the number of trials within each category, and the horizontal dashed line represents CPR = 1.



**Fig. 7** Predicted mean CPR values from the mixed model analysis for the different fertilizer practices used in the trials. Points show mean values for each category, with associated standard errors obtained from the linear mixed model calculated with emmeans (see Section 2). Values above the x-axis indicate the number of trials within each category, and the horizontal dashed line represents CPR = 1.

weed competition was generally low, perhaps because of the impacts of other weed management approaches such as crop rotation or previous mechanical control, or that herbicides were ineffective at controlling weeds in one or more of the trial treatments.

Crop mixtures are frequently used as a chemical-free method of weed control, particularly in organic systems; weed control is generally improved, however, only when compared with monocultures of the less weed-suppressive component, typically the legume, and not the more competitive component, typically the cereal (Gu et al. 2021). Further, weed suppression by intercrops is optimized by using additive rather than replacement sowing designs and, in the latter situation, homogenous mixtures compared with row intercrops (Gu et al. 2021). The trials in our dataset varied in sowing patterns, which might have added to the variability in herbicide response. Our experience of gathering data through a participatory approach shows the importance of collecting complete information about crop inputs; in our case, we did not gather details about whether herbicide was applied to all crop combinations or only a subset of plots (for example, only the monoculture crops), which limits the interpretation of herbicide effects.

All the mixtures in our dataset included legumes. As legumes and cereals exploit different N sources in mixtures (Cowden et al. 2021), it is common practice to reduce the quantity of N fertilizer in cereal-legume mixtures to a lower level that still supports cereal crop growth while minimizing the suppression of legume root nodulation (Jensen et al. 2010; Li et al. 2020b; Mei et al. 2021). The lack of added benefit of inorganic N fertilizer for CPR values suggests that the N requirements of the cereal component were satisfied by background soil N supply, including both previous fertilizer treatments and potential residual effects of earlier legume crops. Alternatively, adding inorganic N may have reduced N fixation in the intercrop by a counterbalancing amount. The beneficial effect of organic N fertilizer on CPR values in the current study is intriguing, and while there is no clear immediate explanation, there might be a number of factors driving this result. Most prosaically, it might be that sites using organic fertilizer are on relatively poor soils such that fertilizer addition has a disproportionately beneficial effect; although we do not have the data to test this effect directly, our knowledge of these sites indicates this is unlikely to be the driver of this response. Second, the result might relate to the fact that organic inputs are complex, comprising partially decomposed organic matter (animal manure, plant tissues) and mineral nutrients in varying proportions and degrees of availability (summarized in Siedt et al. 2021). It is possible that the effects of organic fertilizers on soil moisture, physical structure, and nutrient retention (Siedt et al. 2021) somehow enhanced crop complementarity by overcoming other nutrient limitations on crop growth, such

as phosphorus, potassium, or micronutrients, or by improving root growth. Alternatively, organic fertilizers might increase soil resource pool diversity, helping reduce crop-crop and weed-crop competition, as per the Resource Pool Diversity Hypothesis (Ryan et al. 2009; Smith et al. 2010). Finally, although no three-species mixtures used inorganic N (Supplementary Material Table 5), higher CPR for organic N trials was unlikely to be a result of mixture diversity as many more two- than three-species mixtures used organic N.

Our findings of an effect of N addition—albeit of only organic N addition—contrast with meta-analyses conducted by Pelzer et al. (2014) showing that LER was not significantly influenced overall by N fertilizer rate (noting considerable variation between studies) and by Martin-Guay et al. (2018) where no influence of fertilization and intercropping patterns on LER was found. However, our study differs from these previous studies in separating out organic and inorganic N additions, and these previous studies might have detected such a response had this distinction been made (and assuming the datasets would have allowed this comparison). An alternative explanation for the differences in detected responses between studies is their different geographic scale. Martin-Guay et al. also used data from a wide range of intercrop studies which “spanned the globe, from arid (aridity index [AI] b 0.2) to humid environments (AI N 0.65...)” In contrast, we focused very specifically on cereal-legume intercrops grown over a 4-year period in four European countries. Our reduced geographic scope may have reduced variability in our response metric, such that management signals were easier to detect.

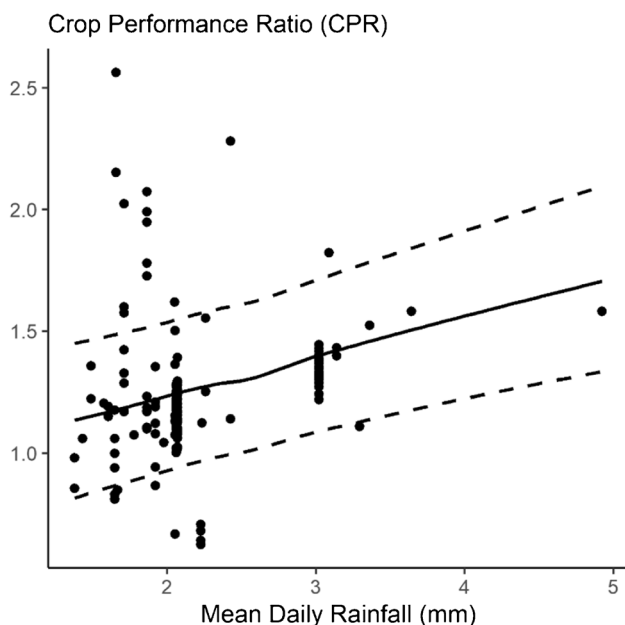
### 3.4 Impacts of climate

Only one weather variable had significant explanatory power for CPR (Table 1). Sites with higher mean daily rainfall exhibited higher CPR values than sites that experienced drier weather (Fig. 8,  $p = 0.025$ ). However, it is clear from the data that high CPR values are obtainable at drier sites, but that low values for CPR are absent at the wetter sites. There was also a weak relationship ( $p = 0.059$ ) with growing degree days (Table 1), which indicated that higher CPR values were a feature of cooler sites.

Our finding of a positive response of CPR values to increased rainfall contrasts with the analysis by Martin-Guay et al. (2018), which showed no effect on LER of environmental conditions (irrigation and the aridity index in non-irrigated intercrops). The weak negative effect of growing degree days indicates that cereal-legume intercrops perform better at cooler, wetter sites, and that these sites deliver the highest CPR values. It is notable that the effects of some factors positively associated with high CPR are not associated with high daily rainfall, in particular the presence of Oats, tillage, and three-species mixtures (Supplementary Material Tables 2, 4, and 6 respectively). However, our result

**Table 1** Mixed effect model output from the analysis of the relationship between CPR and each separate weather variable. Data for weather variables were recorded between sowing date and harvest. *Effect* slope of the relationship, *SE* standard error of the slope, *df* degrees of freedom, *t* t-statistic, *p* probability.

Climate variable	Effect	SE	df	<i>t</i>	<i>p</i>
Mean daily temperature (°C)	−0.001	0.028	20.5	0.037	0.971
Growing degree days (> 5 °C)	−0.0002	0.00014	75.2	1.920	0.059
Mean daily maximum temperature (°C)	−0.009	0.023	18.8	0.387	0.703
Highest temperature recorded (°C)	0.022	0.018	20.9	1.218	0.237
Mean daily minimum temperature (°C)	0.025	0.029	21.2	0.851	0.404
Lowest temperature recorded (°C)	−0.004	0.019	25.5	0.200	0.843
Mean daily rainfall (mm)	0.165	0.071	42.1	2.331	0.025
Total rainfall (mm)	0.0002	0.0004	43.9	0.396	0.694



**Fig. 8** Fitted relationship from the mixed effect model of CPR and mean daily rainfall (mm). Model result:  $CPR = 0.904 + 0.165 \text{ mean daily rainfall}$ ,  $t = 2.331$ ,  $p = 0.025$ . Dashed lines indicate the 95% confidence intervals of the relationship.

might result from our focus on legume-based mixtures, as legumes such as peas and beans—and the N fixation they undertake—are sensitive to dry conditions (Wilson et al. 1985; Loss and Siddique 1997; Prudent et al. 2016; Nadeem et al. 2019). In our study, mixtures with beans in particular showed high CPR values, with pea-based mixtures also performing strongly, and both of these were associated with high daily rainfall (Supplementary Material Table 3).

It is also possible that the association of higher CPR with higher rainfall is driven by a decline in the growth of monocultures under high rainfall (leading to the relationship between CPR and monoculture yield shown in Fig. 3). To test whether the rainfall effect on CPR was in fact due to an effect of rainfall on expected monoculture yield, we analyzed the effect of mean daily rainfall on CPR with expected monoculture yield also included in the model. The effects

of both mean daily rainfall and expected monoculture yield were significant ( $df = 1, 50.9, t = 3.53, p < 0.001$ ;  $df = 1, 57.5, t = 2.32, p = 0.02$ , respectively), as was the interaction between these two factors ( $df = 1, 48.6, t = -2.89, p = 0.006$ ). This indicates that the effect of rainfall on CPR was not driven by an effect of rainfall on monoculture yield. That the response of CPR to rainfall was due to increased intercrop yield rather than reduced monoculture yield suggests that increased rainfall promotes beneficial interactions within the crop mixture, for example through improved uptake of mineral nitrogen and N fixation. These results are also interesting in that they do not match expectations from the SGH, from which we might have expected higher CPR under drier conditions, perhaps reflecting the fact that the beneficial interactions in cereal-legume mixtures which deliver positive CPR values are negatively impacted by water limitation. These results highlight the importance of soil water management to improve resilience to drought and related climate stresses, which are already increasing in frequency and intensity across Europe (Brás et al. 2021).

## 4 Conclusion

Our study is the first attempt, to our knowledge, to quantify the yield benefits of cereal-legume intercropping undertaken at commercially relevant scales for farms across Europe. The findings allow us to answer key questions about the management practices and local conditions affecting intercrops and remove some of the uncertainty about how intercrops will perform in local farm conditions, thus providing reassurance to growers considering growing intercrops.

We have shown that (as per expectations from BEF studies) more is better—although intercropping in general brings yield gains, three crop components give greater CPR values than two—and that crop identity matters, with oats being the better neighbor while lupins are not good companions. Critically, intercrops also clearly have the potential to deliver yield gains with organic nitrogen sources and fewer agrochemical inputs. The apparent lack of effect of herbicide and inorganic N fertilizers on CPR shows, importantly

so given recent increases in fertilizer prices, that crop mixtures could provide a means to reduce input costs and environmental impacts. Other management practices, such as soil tillage, were not sufficiently well represented in our database to draw firm conclusions but our analyses have shown that, irrespective of the management approach, intercropping deliver yield gains on-farm. The mechanistic underpinning of the positive effects on CPR of minimum tillage and clearly separating this from the effects of organic fertilizer are clear targets for future research.

Finally, our analysis shows that climate is an important driver of CPR in cereal-legume intercroppings. Higher rainfall gives larger CPR values, but even in dry conditions, intercroppings outyield the crops in monoculture. This is an important finding in the search for climate-resilient cropping practices that deliver multiple benefits.

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**Authors' contributions** Conceptualization, methodology, and investigation: R.W.B., R.J.P., E.A., J.A.B.-Z., I.B., C.B., J.F.-P., D.G., A.C.N., D.R., S.T., Á.M.V.-F., and A.J.K. Data curation and formal analysis: R.B., R.J.P., and A.J.K. Writing—original draft preparation: R.B., R.J.P., and A.J.K. Writing—reviewing and editing: R.W.B., R.J.P., E.A., J.A.B.-Z., I.B., C.B., J.F.-P., D.G., A.C.N., D.R., S.T., Á.M.V.-F., and A.J.K. Funding acquisition and project administration—R.W.B., R.J.P., E.A., J.A.B.-Z., I.B., C.B., J.F.-P., D.G., A.C.N., D.R., S.T., Á.M.V.-F., and A.J.K.

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**Data availability** The datasets generated and analyzed are available from the corresponding author on reasonable request.

## Declarations

**Ethics approval** Not applicable

**Consent to participate** Not applicable

**Consent for publication** Not applicable

**Conflict of interest** The authors declare no competing interests.

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