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Crop diversity enhances drought tolerance and reduces environmental impact in commodity crops

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ABSTRACT

Key challenges in agriculture include enhancing tolerance to extreme climatic events and reducing environmental impacts. While diversified crop rotations and cover crops are known to reduce pest incidence and improve soil health, their combined effects on production, especially during extreme droughts, remain unclear. To examine the impact of crop rotation diversity and cover crops on grain yield and pesticide footprint (measured by the Environmental Impact Quotient, EIQ) of rainfed maize and soybean in both normal and extremely dry years, we applied mixed-effects models to data from 1777 fields in Argentina. Overall, increasing crop rotation diversity reduced field EIQ, with the impact on grain yield varying based on crop type, nitrogen fertilization, and year. Maize yield improved with crop rotation diversity in the dry year, particularly with low nitrogen fertilization, reaching yields similar to those in normal year. Soybean yield, instead, was unaffected by either crop rotation diversity or cover crops. While grain yields of crops following cover crops and fallow were comparable, fields with cover crops showed a reduction in EIQ of up to 20 %. Diversified crop rotations emerge as an effective management strategy to alleviate drought and low nitrogen fertilization's adverse effects on maize yield. Additionally, cover crops help reduce agriculture's environmental impact without diminishing maize and soybean production. Our findings underscore the importance of crop diversification in developing a more sustainable agricultural system with reduced inputs and enhanced drought resilience.

1. Introduction

Rainfed agricultural systems face two important challenges: maintaining grain production in the context of climate change and reducing environmental impacts. Climate change is increasing the frequency, magnitude and duration of drought events in several regions of the world, and projections indicate that this trend will continue (Cook et al., 2018; Li et al., 2009). Global projections estimate drought-related yield reductions of about 50 % by 2050 and 90 % by 2100 for major cereal crops, threatening food security for millions of people (Li et al., 2009). Another concern with rainfed agriculture is the extensive use of pesticides, which can contaminate water, soil, and air, pose toxicity risks to non-target organisms, and harm human health (Tilman et al., 2001; Tudi et al., 2021). Large-scale monoculture systems exacerbate drought sensitivity and pesticide use because homogeneity limits biological functions, leads to inefficient water use, and facilitates the colonization

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of pests and diseases (Degani et al., 2019; Marini et al., 2020; Woźniak, 2019). Therefore, increasing crop diversity can mitigate the consequences of rainfed agriculture (Lechenet et al., 2014).

A strategy to diversify conventional agriculture fields is to increase the number of crop species that are rotated in a same field. Each crop species contributes to the functioning of the ecosystem in different ways. For example, legumes fix atmospheric nitrogen and improve phosphorus availability, while grasses produce large amounts of biomass (Sassenrath and Farney, 2019). Consequently, diversified crop rotations result in higher soil organic carbon stocks, soil organic matter, infiltration, and greater efficiency in the use and availability of water and nutrients (Andrade et al., 2023; Novelli et al., 2017; Semmartin et al., 2023; Woźniak, 2019). The implementation of these soil improvements can enhance the drought tolerance of crops, i.e. increase yields in drought conditions in comparison to those with a low tolerance (Renwick et al., 2021). Furthermore, the alteration of crop species from one year to another has the potential to disrupt the life cycle of weeds, insects, and diseases, thereby reducing their prevalence and the necessity for pesticide application (Andrade et al., 2017; Woźniak, 2019). Previous studies have indicated that diversified crop rotations and intensified land use (i.e. more crops sown per year) have the potential to enhance grain yield, improve resilience to abiotic stress, and reduce the need for pesticide and fertilizer application (Davis et al., 2012; Degani et al., 2019; Gaudin et al., 2015; Marini et al., 2020). However, the majority of current studies have been conducted in trial field settings, which may not fully represent real-world scenarios.

Cover crops represent an alternative to replace fallow land and offer a variety of benefits to the subsequent main crop. The use of cover crops has been demonstrated to prevent soil erosion, provide nutrients, increase soil organic carbon, and improve water infiltration and retention (Basche et al., 2016; Semmartin et al., 2023). Furthermore, they are frequently employed for weed management purposes, as they compete with weeds, impede their establishment, and reduce the necessity for herbicide applications (Andrade et al., 2017; Finney et al., 2017). A much-debated question is whether cover crops affect grain yield and tolerance to abiotic stress. Some studies have indicated positive effects (Degani et al., 2019; Gaudin et al., 2015; Marini et al., 2020), while others report the opposite (Deines et al., 2023; Garba et al., 2022). It has been observed that they can be particularly problematic in arid regions and during droughts, as their transpiration may off-set any benefits on infiltration enhancement and direct evaporation reduction, curtailing soil water available for the following main crops, thereby reducing their productivity (Garba et al., 2022). While cover crops can play a key role in achieving sustainable agricultural production, further research is necessary to optimize their benefits on crop yields.

Since the beginning of the 21st century, the Argentine Chaco-Pampean region has experienced a 2.8-fold increase in grain and oil production at the expense of increasing environmental degradation (Andrade, 2017; Ministerio de Agricultura, Ganadería y Pesca, 2024). Argentina's rainfed agriculture is based on a rotation of summer crops with minimal diversification and dominated by soybean and maize, extended winter fallows, low levels of fertilization with a negative balance, and no-till farming with high rates of herbicide use, particularly glyphosate, associated with genetically modified organisms (GMOs) cultivars (Jobbágy et al., 2021; Leguizamón et al., 2023). The low fertilization rates and the lack of diversification in crop rotations have a deleterious impact on soil conservation, which has become a matter of increasing concern (Caviglia and Andrade, 2010). Moreover, the excessive utilization of herbicides has the potential to contaminate a multitude of environmental matrices, including soil, groundwater, precipitation, surface water and atmospheric air (Lupi et al., 2019; Rivas-Garcia et al., 2022). Nevertheless, this low fertilization strategy is still able to sustain average global grain yield, what can be attributed to the high-quality soils in this region (Jobbágy et al., 2021). This characteristic establishes Argentinean agriculture as an interesting case study, as there is a significant yield gap and a clear necessity for improvements in sustainability (Aramburu Merlos et al., 2015). The potential of crop rotation and cover crops to increase grain yield and production sustainability has been evaluated in multiple trial settings in Argentina (Andrade et al., 2023; Novelli et al., 2017; Semmartin et al., 2023), yet few studies have analyzed a regional-scale commercial field database for this purpose.

Our aim is to analyze the effects of crop rotation diversity and the use of cover crops on single-cropped maize (*Zea mays L.*) and single-cropped soybean (*Glycine max L.*) grain yield, drought tolerance, and environmental impact. We hypothesize that diverse crop rotations and the use of cover crops enhance soil characteristics that benefit the production of the main crops, while reducing the environmental impact by limiting pest prevalence. We expect a positive relationship between crop rotation diversity and grain yield, particularly during the dry year, and a negative relationship with field EIQ. In particular, we expect fertilization to be an important covariate in maize yield, as the effects of crop diversity on yield would be partly due to its effects on soil fertility. Furthermore, we expect that main crops preceded by cover crops will have higher grain yields, especially during the dry year, and lower field EIQ than winter fallow. To test these hypotheses, we analyzed a large database of a farmers' association in the Chaco-Pampean region of Argentina. To assess the influence of crop rotation diversification and cover crops on drought tolerance, we compared the response of variables between a normal rainfall year and a drought year, leveraging the opportunity presented by the most intense and widespread drought of the last four decades. The environmental impact was estimated using fields EIQ, which is based on the toxicity of pesticides and the dose applied (Kovach et al., 1992).

2. Material and methods

2.1. Study area

The Argentinean Chaco-Pampean region (Fig. 1) is one of the most productive regions in the world. This high productivity is due to the dominance of the Mollisols, with Argiudols and Haplustols being the most represented groups (Caviglia and Andrade, 2010). These soils allow farmers to produce with very low fertilization rates (Koritschoner et al., 2023; Leguizamón et al., 2023). Glyphosate-resistant soybean and maize are the most common crops, in rotations of maize/soybean, maize/wheat-soybean, and occasionally soybean monocultures (Table 1). Cover crops occupy a small portion of cultivated lands, but their use has increased in recent years (Bolsa de Cereales, 2023).

Precipitation decreases from E to W of the Argentinean Chaco-Pampean region and it is concentrated during the summer (December to March) and the beginning of autumn (March to June) with a decline during winter (June to September), particularly towards the central-western and northern zones (Caviglia and Andrade, 2010). There is a well-defined boundary for rainfed agriculture at a mean precipitation value of 700 mm year^{-1} in the north-south central strip of the region, while the average annual precipitation in the south-western is 400 mm year^{-1} and 1300 mm year^{-1} in the north-eastern zone (Atlas Climático SMN). The average annual temperature drops steadily from 22° C in the north to 13° C in the southern portion of the Argentinean Chaco-Pampean region (https://climatecharts.net/).

We used precipitation anomalies during the agricultural years to determine extreme dry and normal years over a 10-year time window. The anomaly defines the degree to which precipitation deviates from its mean state to detect dry years (i.e., extremely negative precipitation anomalies) and normal years (i.e., precipitation anomalies close to zero) based on the approach presented by Whitworth-Hulse et al., (2023). The 2021–22 agricultural year (from October of 2021 to September of 2022) in the Argentinean Chaco-Pampean region exhibited near-average precipitation conditions. The spatial distribution of rainfall followed the typical heterogeneous pattern, with minor surpluses and deficits (Fig. 1), reflecting the region's precipitation variability (Magliano et al., 2015).

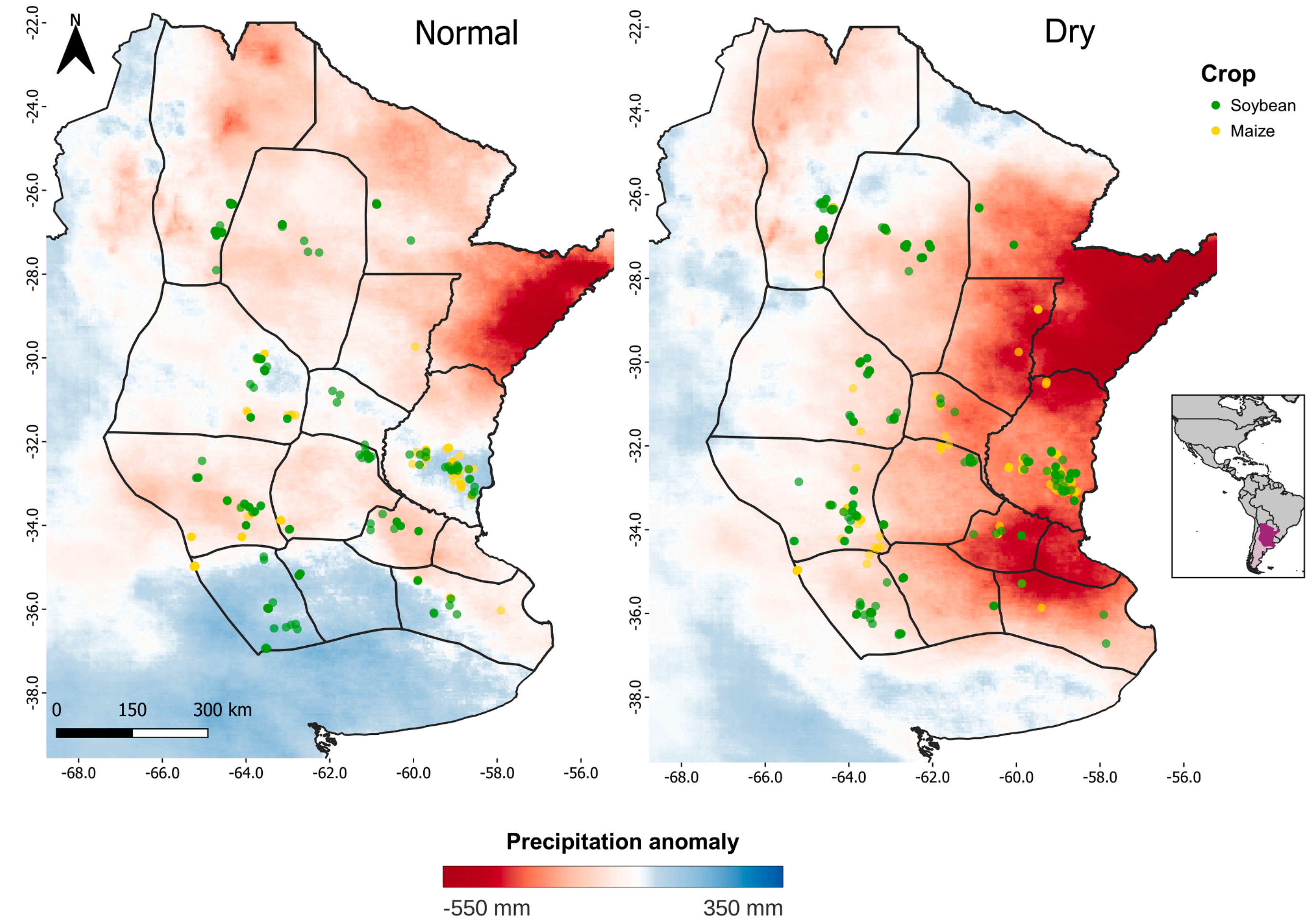

Fig. 1. Absolute precipitation anomalies for the normal (2021–22; left) and dry (2022–23; right) years at the study site. The absolute anomaly is defined as the difference between the cumulative precipitation of the growing season (September to March) and the average precipitation for the same period over the previous ten years. Precipitation deficits are represented with red, precipitation surpluses with blue, and areas of no anomaly with white. The circles indicate the location of some of the study fields, which were cropped with soybean (green) and maize (yellow). The black lines delineate the boundaries of CREA regions.

Table 1
Frequency of crop rotation sequences and the species used as cover crops for the studied fields. In order to facilitate the comprehension of the crop rotation diversity index, the inverse of Simpson's diversity index (SDI) was incorporated for each crop rotation sequence. This calculation was based on a five-year sequence. Abbreviations: S1: single-crop soybean, S2: double-crop soybean, MZ: maize, W: wheat, CC: cover crop.

Crop rotation sequences (n = 1013)	**Frequency (%)**	**SDI**
W-S2/MZ/S1	34	2.88
S1/M	30	1.92
W-M/S1	11	2.90
W-S2/S1	6	1.88
CC-S1/MZ/W-S2	6	3.55
W-S2/W-S2/MZ	5	2.45
CC-MZ/S1	5	4 (with different cc species)
Others	3	
Species used as cover crop (n = 153)	**Frequency (%)**	
Rye (*Secale cereale L.*)	31	
Vicia sp.	12	
Mixtures (legumes+poaceas)	9	
Vetch (*Pisum sativum L.*)	2	
Unknown	46	

Consequently, in terms of precipitation, the year 2021–22 was designated as the "normal year" for this study. In contrast, the 2022–23 agricultural year (from October of 2022 to September of 2023) was one of the driest on record in the Chaco-Pampean region (Fig. 1). The cumulative precipitation losses in the study area during the 2022–23 growing season (September to March) averaged between −500 and −100 mm, compared to the average of the ten previous years (Fig. 1). The most impacted area by the drought was the Nucleuos-Pampean region, which is one of the most productive areas worldwide. This resulted in a reduction in average soybean yield of 35 % and in average maize yield of 25 % compared to historical yields (Ministerio de Agricultura, Ganadería y Pesca, 2024). Consequently, the year 2022–23 was designated as the "dry year" in this study.

2.2. Data collection

The data were collected and systematized by CREA (https://www.crea.org.ar/), a non-profit civil association that includes more than 2200 agricultural companies that share their experience and knowledge of agriculture. The database included information on crop yield (kg ha^{-1}), crop rotation sequence (Table 1), field location, field area (ha), region (10 regions were considered), sowing seed density and date, crop genetic variety, fertilizer application (kg ha^{-1}), and for year 2021–22 the Field Use Environmental Impact Quotient (EIQ). The fields' EIQ values were calculated by the CREA team using the application of pesticides reported by the farmers (i.e. active ingredient; toxicity rate;

product measurement unit; application area), based on Kovach et al., (1992).

We estimated the crop rotation diversity in sequences of five years. For example, for the rotation diversity index of 2021–22, we considered the crop sequence from 2017–2018 to 2021–2022. Rotation diversity was estimated using the inverse of Simpson's diversity index, calculated as: $SDI = 1/\sum pi^2$, where pi is the proportion of each species in the rotation. For example, a five-year rotation sequence comprising six crops in total — soybean/maize/soybean/wheat-soybean/maize — where soybean proportion is 3/6, maize is 2/6, and wheat is 1/6, the SDI calculation is $1/((3/6)^2 + (2/6)^2 + (1/6)^2) = 2.571$. A monoculture is assigned a SDI value of one, whereas a five-year sequence comprising different species in each year is assigned a value of five. Achieving high values of SDI in Argentinean rainfed agriculture requires intensification of crop production, due to the low richness of main crops employed. Consequently, crop sequences with high values of SDI also exhibit high values of crop intensification. The winter management of the study years was extracted from the rotation sequences and was classified as cover crop or winter fallow. Since we were interested in analyzing maize and soybean as a single crop, fields with grain production in the winter of the study years were excluded from the analysis.

2.3. Data analysis

We fitted four linear mixed-effects models, two to explain the yield (kg ha^{-1}) and two to explain the EIQ of single-cropped maize and soybean, one for each crop. These models assumed a Gaussian error distribution and homogeneity of variances (lme4 package, lmer function, Bates et al., 2015; R Core Team, 2023). Both assumptions were tested through diagnostic plots and quantitatively. The fixed effects were the variables of interest, specifically crop rotation diversity (SDI value) and winter management (winter fallow (0) or cover crop (1)), with both variables interacting with the year (normal (0) or dry (1)), and other important management variables, including sowing seed density (pl m^2), sowing date (Julian date), nitrogen (N) and phosphorus (P) fertilization (kg ha^{-1}; N only for maize), and field area (ha). Additionally, the maize yield model considered the interaction of N fertilization with crop rotation diversity. Nitrogen fertilization was excluded from soybean models because this practice is uncommon in soybean crops, due to the presence of N-atmospheric fixing symbiotic bacteria. The influence of crop genetic variety and the different regions, which have distinguished weather and soil characteristics, were considered as non-nested random effects in the models. Statistical inference was performed using multi-model inference based on Akaike's Information Criterion (AIC) (Harrison et al., 2018). The model with the minimum AIC was selected from all possible combinations of predictor variables (MuMIn package, dredge function, Bartón, 2019). From this selection, we determined which predictors explained the predicted variable. Relative importance (RI) was calculated for each predictor by summing the Akaike weights across all models containing the predictor, which determines the relevance of the variable in explaining the predicted variable (MuMIn package, sw function). We considered high evidence when the RI was higher than 0.85, moderate evidence when the RI was between 0.84 and 0.65, low evidence when the RI was between 0.64 and 0.50, and no evidence when the RI was lower of 0.49. All analyses were performed in R (R Core Team, 2023).

3. Results

We analyzed a total of 1777 fields covering 148,466 ha of the 2021–22 (normal year) and 2022–23 (dry year) agricultural years, with 1175 fields cropping soybean and 602 cases with maize. In the normal year, maize yields averaged 6725 ± 2661 kg ha^{-1} (mean ± SD), while soybean yields averaged 3581 ± 883 kg ha^{-1}. In contrast, in the dry year maize yields averaged 4646 ± 2401 kg ha^{-1}, while soybean yields averaged 1788 ± 944 kg ha^{-1}. The mean yield losses resulting from drought conditions, as compared to the normal year, were 31 % and 50 % for maize and soybeans, respectively, with some regions reaching losses of up to 66 % for both crops. The field EIQ averaged 104 ± 33.3 and 96.5 ± 31.3 for maize and soybean, respectively. The N application in maize was 72.1 ± 42.9 kg ha^{-1} and 67.2 ± 40.6 kg ha^{-1} for the normal and dry year, respectively.

Crop rotation diversity was identified as a significant explanatory factor for maize yield and field EIQ for both crops. Furthermore, the interaction between N fertilization and crop rotation diversity had a strong effect on maize yield, with a more notable impact observed in the dry year compared to the normal year (Table 2). The mean maize yield increased by 113 ± 147 kg ha^{-1} (mean ± SE) and 741 ± 164 kg ha^{-1} for each one-point increase in diversity for the normal and the dry year, respectively (Fig. 2(A)). Notably, fields with diversity near to 5 yielded similar to the mean yield observed during the normal year. Furthermore, when low levels of N fertilizer were applied (below 75 kg ha^{-1}), maize yield increased on average by 1009 ± 159 kg ha^{-1} and 381 ± 170 kg ha^{-1} for each additional diversity level observed in the dry and normal year, respectively (Fig. 3). Conversely, when high levels of fertilizers were applied (more than 75 kg ha^{-1}), maize yield increased on average by 470 ± 220 kg ha^{-1} but decreased by 158 ± 184 kg ha^{-1} for each one-point increase in diversity, for the dry and normal year, respectively (Fig. 3). With respect to the EIQ of maize crops, there was an average decrease of 4.6 ± 3.46 points with each additional level of crop rotation diversity (Fig. 2(B)). The influence of crop rotation and winter management was not important in the context of soybean yield, with field management practices such as sowing density, sowing date, fertilization, and field area observed to have a more pronounced influence (Table 2; Fig. 2(C), Fig. 4(C)). Instead, the soybean field EIQ exhibited a decrease of 5.68 ± 2.54 for each point of rotation diversity increase (Fig. 2(D)).

The evidence suggested that the use of cover crops as a predecessor had no impact on maize and soybean yield (Table 2; Fig. 4(A, C)). Instead, strong evidence indicated that maize preceded by a cover crop exhibited lower field EIQ (85.3 ± 6.34) in comparison to winter fallow (106.3 ± 3.92; Table 2; Fig. 4(B)). Nevertheless, no evidence was found to suggest that the use of cover crops or winter fallow preceding soybean crops resulted in differences in field EIQ (Table 2). However, a trend towards a reduction in field EIQ was observed when soybean was preceded by cover crops (80.7 ± 8.53 winter fallow; 74.6 ± 11.1 cover crops) (Fig. 4(D)).

4. Discussion

The impact of crop rotation diversity on yield is dependent on the target crop species, precipitation conditions and, in the case of maize, the application of N. During the dry year, maize yield showed a strong increase as diversity increased, whereas this effect was insignificant during the normal year (Fig. 2(A)). This effect was more pronounced under low fertilization rates (Fig. 3). Soybean yield was not affected by any of the studied variables, except for the differences between the dry and the normal year (Table 2). In contrast to the initial hypothesis, both maize and soybean crops that were preceded by cover crops had similar yields to crops that were preceded by winter fallow (Fig. 4). As we expected, maize and soybean field EIQ decreased as diversity increased (Fig. 2). Additionally, maize EIQ was reduced by 20 % when preceded by cover crops in comparison to winter fallow (Fig. 4(B)).

4.1. Maize yield response to crop rotation diversity

Our results showed that maize yield is sensitive to rotation diversification. In order to accomplish the highest level of diversity in rotations, it is necessary to implement an intensification strategy with more than one crop per year, something that can be achieved through the use of winter crops as main or service crops (Table 1). The implementation of diversified rotations improves soil characteristics, including infiltration,

Table 2
Results from the mixed-effects models of the influence of crop rotation diversity (diversity, SDI index), winter management (winter fallow (0) or cover crop (1)), and year (normal (0) or dry (1)) on yield (kg ha^{-1}) and environmental impact quotient (EIQ) of maize and soybean crops. The models included sowing seed density (pl m^2), N and P fertilization (kg ha^{-1}), field area (ha), and sowing date (Julian date) as important explicatory co-variables of yield and EIQ. The influence of crop genetic variety and the different regions were considered as non-nested random effects in the models. The best models were selected by comparing the Akaike Information Criterion (AIC) values of all the possible combinations of predictors (see Material and methods). The relative importance of a predictor is the sum of the Akaike weights of all models that include the predictor. Parameter estimate and standard error are shown only when the predictor is included in the optimal model. A tick (-) is included when the predictor was not evaluated in the model.

	Maize				Soybean			
	Yield (n = 602)		EIQ (n = 253)		Yield (n = 1150)		EIQ (n = 284)	
	Relative importance	Parameter estimate	Relative importance	Parameter estimate	Relative importance	Parameter estimate	Relative importance	Parameter estimate
Fixed effects								
Intercept	-	−1013 (1100)	-	118.3 (10.32)	-	3258 (268.1)	-	49.92 (15.27)
Diversity	1	719.7 (255.3)	0.51	−4.601 (3.314)	0.49		0.66	−4.925 (2.366)
Cover crop	0.54		1	−20.99 (5.837)	0.63		0.42	
Dry year	1	−3883 (575.8)	-	-	1	−1671 (45.81)	-	-
Diversity • Dry year	0.98	627.6 (203.8)	-	-	0.21		-	-
Diversity • N fertilization	0.94	−8.686 (3.171)	-	-	-	-	-	-
Cover Crop • Dry year	0.32		-	-	0.29		-	-
Sowing seed density	1	83.70 (12.07)	0.28		0.58	7.767 (4.690)	1	1.196 (0.260)
N fertilization	1	30.84 (8.955)	0.33		-	-	-	-
P fertilization	0.27		0.36		0.97	10.13 (3.311)	0.48	
Field area	0.30		0.89	0.087 (0.035)	0.96	1.151 (0.393)	0.32	
Sowing date	0.28		0.83	−0.037 (0.016)	0.89	−0.636 (0.254)	0.46	
Random effects (sd)								
Region		1952		7.315		540.9		23.23
Crop genetic variety		458.4		7.947		156.3		17.96
R^2								
Conditional		0.686		0.253		0.652		0.728
Marginal		0.246		0.149		0.452		0.050

porosity, and soil organic carbon (SOC) levels (Andrade et al., 2023; Novelli et al., 2017). These characteristics enhance soil water permeability and storage (Degani et al., 2019). Consequently, during the dry year, fields with diversified rotations exhibited comparable yields to those observed during the normal year (Fig. 2(A)). Similar findings were reported in previous studies, particularly in long-term rotation diversity experiments, which revealed an even greater maize drought tolerance (Degani et al., 2019; Gaudin et al., 2015; Marini et al., 2020; Renwick et al., 2021).

Furthermore, maize yields in fields with N fertilization levels below 75 kg ha^{-1} and species diversity levels above 3 (at least three different species, Table 1) are comparable to those in fields with higher N fertilization levels. This may be explained by the fact that a high diversity of species in the crop rotation increases the availability of N, enhances its use efficiency, facilitates recycling, reduces leaching; whereas the inclusion of legumes facilitates the incorporation of atmospheric N (Riedell et al., 2009; Wade et al., 2020). Consequently, increasing crop rotation diversity can be an essential management strategy to produce with low inorganic fertilizer application without repercussions on maize production. Moreover, previous studies have indicated that the long-term implementation of diversified crop rotation (at least 35 years) leads to an increase in the benefits in terms of maize yield under conditions of low fertilization or drought (Renwick et al., 2021; Smith et al., 2023). It is essential to conduct long-term studies of diversified rotation effects on soil nutrient storage, particularly in regions where there is evidence of soil nutrient depletion.

The lack of effect of crop rotation diversity on maize yield during the normal year (Fig. 2(A)) may be attributed to the fact that maize yield is more responsive to water availability and fertilization, thereby attenuating the influence of crop rotation diversity. However, when some of these resources are limited, crop rotation diversification may be essential to avoid loss of maize production. For example, during the dry year with restricted fertilization, where water and N are scarce, maize yield exhibited a more pronounced increase than in any other condition (Fig. 3). In other words, the benefits of crop rotation diversified on maize yield are significant when essential resources are limited.

4.2. Maize yield response to the use of cover crops

The impact of winter cover crops on summer crop yield is actually a subject of extensive debate. The use of cover crops has been observed to enhance soil structural stability, water infiltration, and the availability of nutrients, which positively impacts on the yield of the main crop (Alvarez et al., 2017). However, our analysis revealed no significant differences between the use of cover crops and winter fallow in terms of maize and soybean yield. The implementation of cover crops has been observed to have a detrimental impact on the yield of subsequent summer crops due to competition for water and nutrients, particularly under drought conditions (Alvarez et al., 2017; Deines et al., 2023; Garba et al., 2022). Conversely, our findings indicate no evidence that cover crops negatively affect maize and soybean yield during the dry year, thereby suggesting that the potential benefits of cover crops for soil and pest management may override any other effects reducing productivity.

One aspect to consider is that cover crops have been employed in the region under study for a relatively brief period, spanning approximately five years. It is known that the use of cover crops exerts a cumulative influence on soil over time, with effects that may be either beneficial or detrimental. For example, the use of long-term cover crops has been shown to increase SOC levels (Poeplau and Don, 2015). Conversely, fields that employ cover crops have been observed to exhibit a 50 % reduction in soil nitrate pool compared to winter fallow, which is

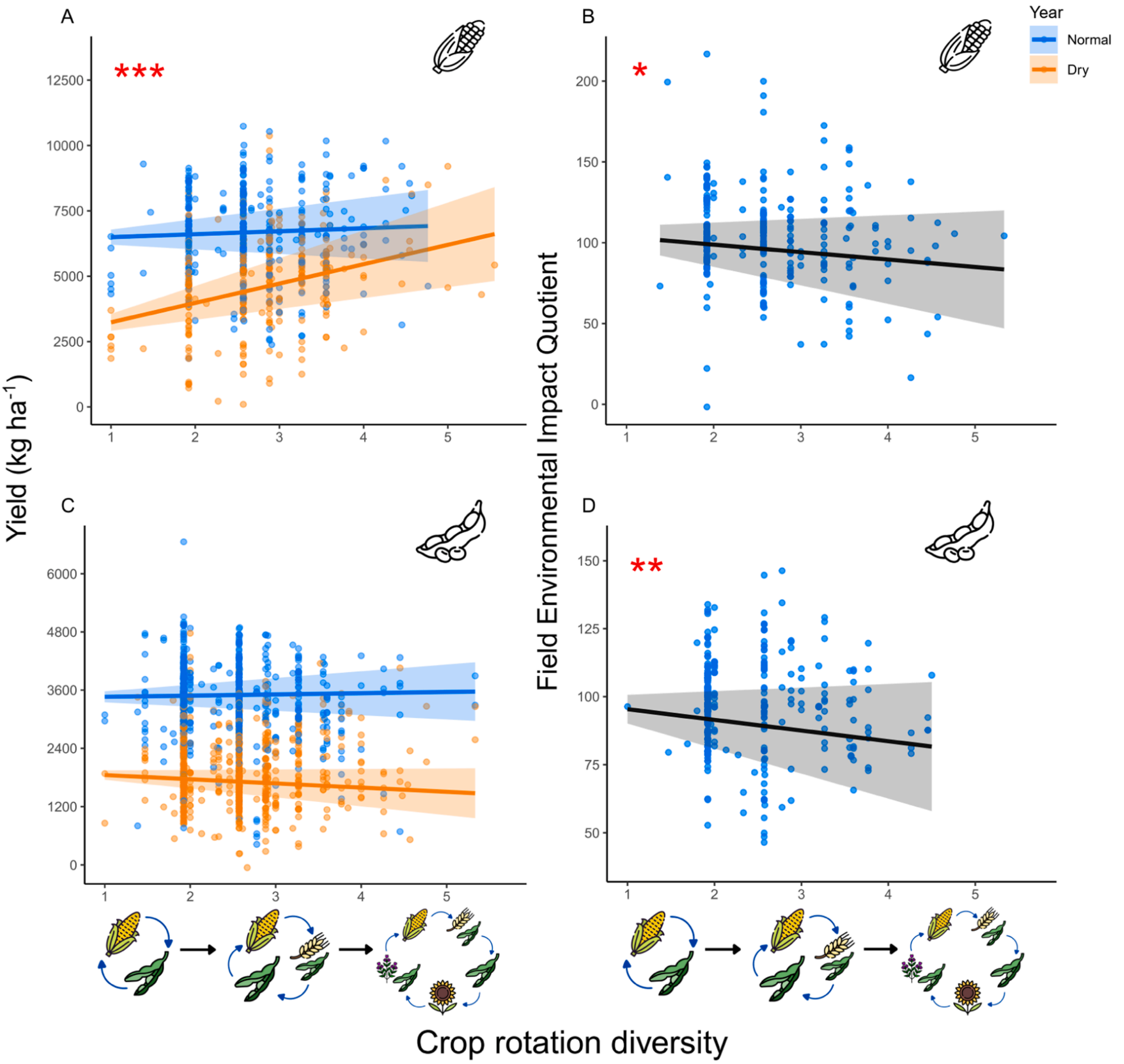

Fig. 2. Crop rotation diversity improves maize yield during a dry year and reduces environmental impact. Dispersion plots with regression lines and 95 % confidence intervals of the yield (kg ha^{-1}) of maize (A) and soybean (C) in relation to the crop rotation diversity (inverse of Simpson's diversity index), and the environmental impact quotient (EIQ) of maize (B) and soybean (D) in relation to crop rotation diversity for the normal (in blue) and the dry year (in orange). The red asterisk indicates the level of evidence for the relations: *** high evidence (Relative importance (RI) > 0.85), ** moderate evidence (0.84 > RI > 0.65), * low evidence (0.64 > RI > 0.50), and empty cells indicate a lack of evidence (RI < 0.49).

especially concerning in an underfertilized region like the Chaco-Pampean (Alvarez et al., 2017). Therefore, it is essential to conduct long-term trials of cover crops to assess the potential positive and negative impacts on nutrient reserves and soil health, especially in regions with low fertilizers application.

A limitation of this study is that the database that was used does not distinguish between leguminous and non-leguminous cover crops. Consequently, it is not possible to determine the effect of each crop category on summer crop yields. For example, previous studies have found a positive effect of leguminous cover crops on maize yield, whereas no such effect was observed with non-leguminous crops (Finney et al., 2017; Qin et al., 2021; Zhao et al., 2022). It is possible that the positive effect of leguminous cover crops is offset by the negative effect of non-leguminous cover crops. Additionally, it should be noted that this analysis was unbalanced, with the majority of fields utilizing winter fallow prior to the main crop, at approximately 90 % prevalence. In some areas of the Chaco-Pampean region, cover crops are not employed, as it is known that they have a detrimental effect on summer crops. Consequently, these areas were not represented in the study, which may have introduced a degree of bias to the analysis.

4.3. Why was the soybean yield not affected?

In contrast, the yield of soybeans was not influenced by the diversity of rotations or the use of cover crops, a finding that aligns with those of previous studies (Alvarez et al., 2017; Hisse et al., 2022). This indicates

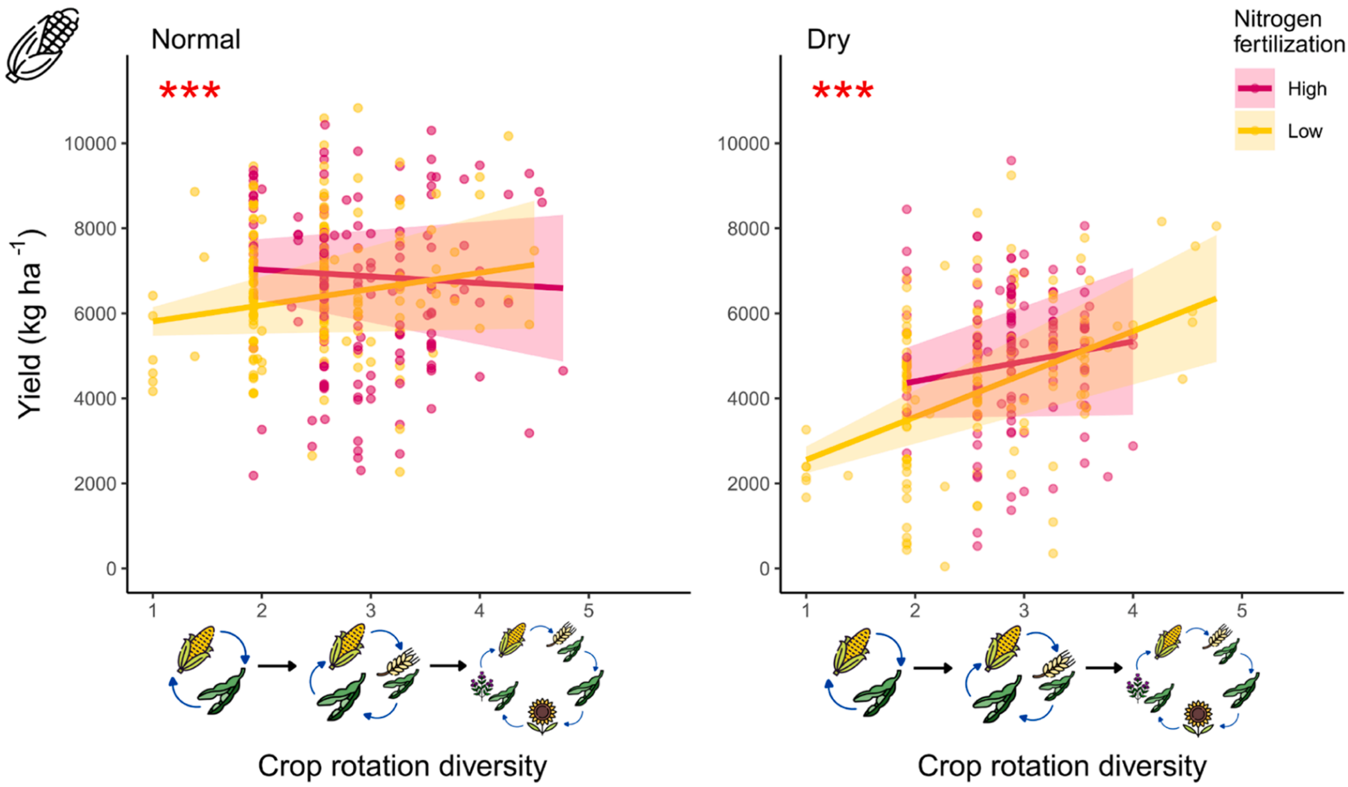

Fig. 3. Crop rotation diversity increases maize yield under conditions of low nitrogen fertilization. Dispersion plots with regression lines and 95 % of confidence intervals of maize yield (kg ha^{-1}) in relation to crop rotation diversity (inverse of Simpson's diversity index), for the normal (left box) and the dry year (right box). For illustrative purposes, N fertilization was categorized. Fields with low N fertilization (yellow) were applied with 75 kg ha^{-1} or less, and high N fertilization (pink) were applied with more of 75 kg ha^{-1}. The red asterisk indicates the level of evidence for the relations: *** high evidence (Relative importance (RI) > 0.85), ** moderate evidence (0.84 > RI > 0.65), * low evidence (0.64 > RI > 0.50), and empty cells indicate a lack of evidence (RI < 0.49).

that as a result of its symbiotic N-fixation, soybean may be relatively insensitive to soil with higher levels of available N, a characteristic that can be observed in fields that implement diversified rotation and cover crops. Additionally, the N-fixation process is particularly susceptible to drought conditions, thereby representing a limitation of both water and N (Freitas et al., 2022). Considering that soybean crops are usually not fertilized with N, this may explain why the drought affects soybean yield to a greater extent than maize. The enhancements to soil quality resulting from diversified crop rotation and cover crops may be unable to offset the more pronounced deficiencies in N and water. Another potential explanation is that crop rotation and cover crops are implemented in a relatively short time frame, which may not yet have resulted in the full emergence of their beneficial effects for this crop. Further research is required to better understand the mechanisms behind the observed lack of response in soybeans to soil improvements during drought events.

4.4. Environmental impact reduction

Our results showed that environmental impact decreases with higher diversity and implementing cover crops. Different mechanisms explain how crop rotation and cover crops reduce pest prevalence and consequently field EIQ. For example, altering between host and non-host crop species interrupts the biology cycle of pests and diseases (Liebman and Dyck, 1993). Cover crops increase residue biomass and surface coverage, which intercepts sunlight and impedes the emergence of weed seedlings (Osipitan et al., 2018). Additionally, cover crops may compete with weeds for essential resources and provide refuge and food to herbivore predators during winter (Rowen et al., 2022). The intensified and diversified crop rotation that incorporates winter cover crops has demonstrated efficacy in reducing the frequency of weed proliferation and herbivorous pests, thereby reducing the need for pesticides (Andrade et al., 2017; Lechenet et al., 2014; Rowen et al., 2022). Consequently, lower pesticide application leads to reduced EIQ and environmental impact. To illustrate, the reduction in field EIQ of 27, comparable to the reduction achieved through the utilization of cover crops in previous maize crop, signifies a reduction of 1.27 L ha^{-1} of glyphosate at 66.2 % (Kovach et al., 1992). These results are particularly impactful when viewed in the context of an agricultural sector that typically employs low crop intensification and a high reliance on herbicides (Jobbágy et al., 2021). To our knowledge, no studies have previously reported an association between crop rotation diversity and cover crops with fields EIQ at the regional scale. Our findings indicate that intensified crop rotation with high crop diversity and the use of winter cover crops can be crucial to reduce agricultural environmental impact.

5. Conclusions

Enhancing crop rotation diversity can improve crop yield during a drought year and reduce agriculture's environmental impact. Our results show that incorporating more than three species in a five-year crop sequence can support maize production under limited water and nutrient availability, demonstrating increased drought tolerance. While soybean yield remains unaffected by rotation diversification, it benefits from reduced environmental impact. Implementing diversified crop rotations appears as a sustainable management strategy that allows for reduced nitrogen fertilization and pesticide application without compromising crop performance. Additionally, cover crops can serve as an effective short-term strategy to lessen environmental impact without reducing main crop yield, a promising result given previous findings of yield reduction. Long-term studies are needed to refine management

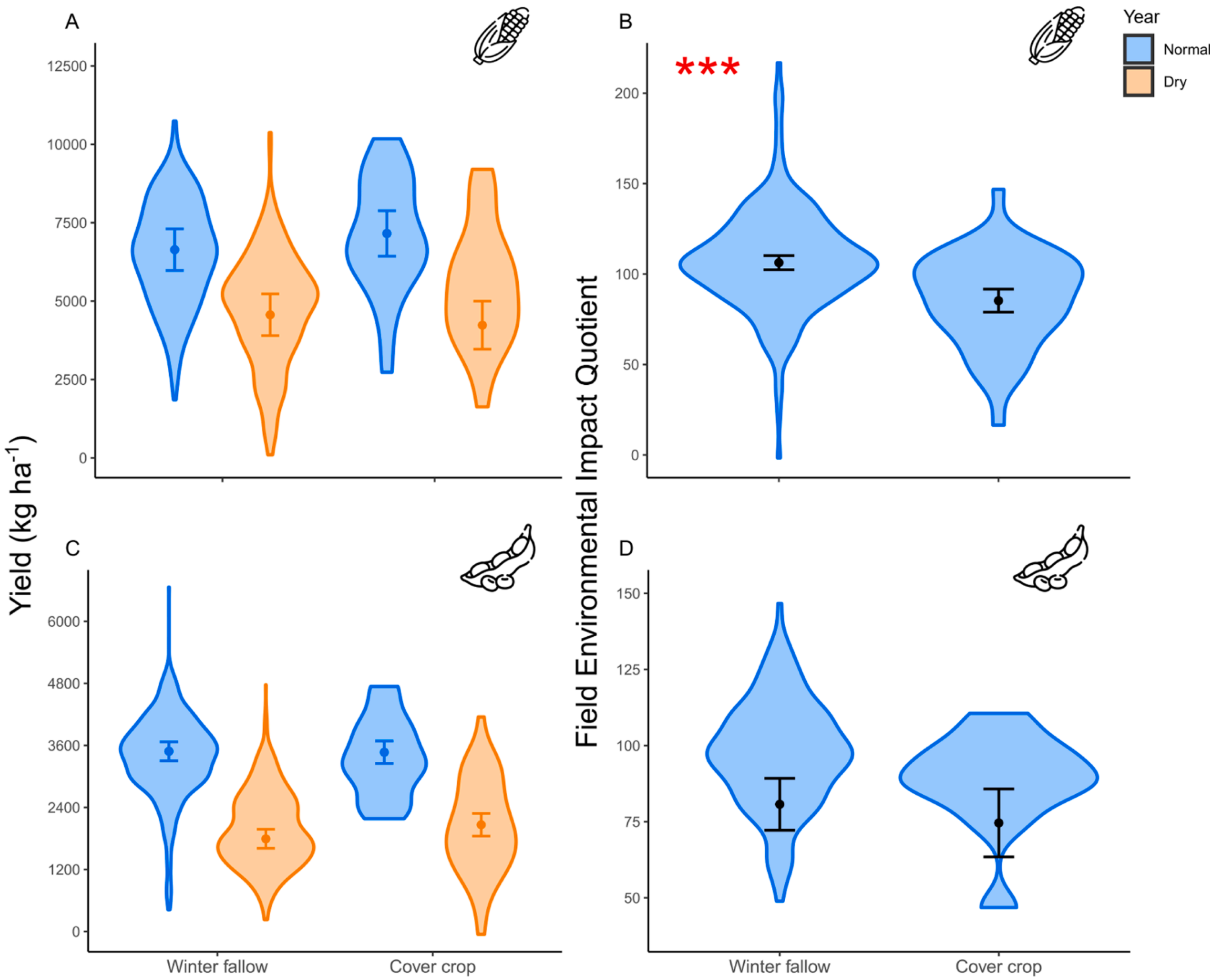

Fig. 4. The use of cover crops reduces the environmental impact of maize. Violin plots with the mean ± SE estimated by the model of the yield (kg ha^{-1}) of maize (A) and soybean (C) in relation to winter management (winter fallow or cover crop), and the environmental impact quotient (EIQ) of maize (B) and soybean (D) in relation to winter management for the normal (in blue) and the dry year (in orange). The red asterisk indicates the level of evidence for the relations: *** high evidence (Relative importance (RI) > 0.85), ** moderate evidence (0.84 > RI > 0.65), * low evidence (0.64 > RI > 0.50), and empty cells indicate a lack of evidence (RI < 0.49).

practices for cover crops to optimize productivity gains. Our observations come from highly polluting fields with negative nutrient balances underscoring the importance of diversified crop rotations and winter cover crops in mitigating agriculture's environmental impact. While the yield effects on maize and soybean may sometimes be neutral, increased crop diversity is vital for safeguarding maize production from drought and low fertilization conditions. Diversified crop systems thus offer a viable alternative to conventional practices, with the potential to reduce inputs and enhance drought tolerance.

CRediT authorship contribution statement

Micheloud Jose Roberto: Writing – review & editing, Conceptualization. **Garibaldi Lucas A.:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Paolini María:** Resources, Data curation, Conceptualization. **Martini Gustavo:** Resources, Data curation, Conceptualization. **Whitworth-Hulse Juan I.:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Satorre Emilio:** Writing – review & editing, Conceptualization. **Goldenberg Matías G.:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Jobbágy Esteban:** Writing – review & editing, Conceptualization. **Leguizamón Yamila:** Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author used "DeepL Write" in order to improve readability and language of the manuscript. After using this tool, the author reviewed and edited the content as needed and take full responsibility for the content of the published article.

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.

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Data availability

The authors do not have permission to share data.

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