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Cultivation of diverse crop species and varieties support yield stability in smallholder farming system

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Research Article

Keywords: Agrobiodiversity, resilience, selection effect, insurance effect, climatic variability, Senegal, Niakhar HDSS

Posted Date: August 24th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10766641/v1

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Additional Declarations: The authors declare no competing interests.

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1. Introduction

Smallholder farmers are among those most exposed to climatic perturbations, including dry spells, droughts, heatwaves and floods. Keeping food supply steady under increasingly extreme and unpredictable climate is one of the ways to reducing hunger and safeguarding rural livelihoods (the 2030 Agenda for Sustainable Development; United Nations, 2015). Yet, the solutions to stabilize yield promoted by agricultural research and development often do not match the reality of the largest global farming population (Laborde et al., 2020; Lowder et al., 2016; Ricciardi et al., 2018). In fact, research on technologies, i.e., chemical inputs, irrigation or storage facilities (Stathers et al., 2020), fail to provide actionable options for people living in chronic poverty, poorly supported by institutions and mainly farming in marginal and rainfed environments (Berhanu et al., 2024; Hadley et al., 2023). In this context, it is urgent to evaluate the contribution of an asset that already lies in these farmers' hands: the diversity of the crops and varieties they cultivate. Understanding whether, and how, this on-farm agrobiodiversity can secure food supply offers a concrete, nature-based pathway to stabilizing yields for those who are on the frontline of climate change.

Building on ecological work on biodiversity–stability relationships, growing evidence indicates that diversifying crops can mitigate climate risks, by increasing both the resistance to climatic perturbations and the temporal stability of yields through time. However, so far, most evidence comes either from field-scale experiments under controlled conditions (e.g., Feng et al., 2024; Gaudin et al., 2015; Mudare et al., 2025; Raseduzzaman & Jensen, 2017; Wang et al., 2026), or from the analyses of regional to national agricultural statistics (Driscoll et al., 2022; Egli et al., 2021b; Renard et al., 2023; Renard and Tilman, 2019). However, the direction and magnitude of the diversity–stability relationship identified at regional or national scales may not operate similarly within farms, where field-level decisions on crops, management, and land allocation introduce additional variability. The few studies conducted at the farm scale mostly use sectorial, panel data coordinated at large organizational scales (Egli et al., 2021a; Menesch et al., 2023), for which extended spatial coverage may come at the expense of data quality and temporal resolution (Fraval et al., 2019; Seidler et al., 2025). Yet, fine-grained, *in situ* data within farms remain scarce. Assessing yield stability requires monitoring efforts sustained over time and assessing each crops' production and cultivated area, data that are both financially and logistically demanding (Pret et al., 2025).

In addition, most research has assessed the stabilizing role of species and varietal diversity in isolation (Gotor et al., 2021), limiting our ability to evaluate their respective impact on agroecosystem functioning (Huang et al., 2024; Prieto et al., 2015; Su et al., 2025; Wang et al., 2026). For instance, Prieto et al., (2015), conducted experiments in perennial grasslands and showed that the richness of species sown in mixtures primarily enhanced productivity, whereas genotypic richness per species primarily enhanced yield temporal stability. Whether such complementarity between levels of diversity exist in cropping systems remains largely untested. This question is particularly relevant in smallholder farming systems

where multiple crop species and varieties are deliberately maintained to address several needs and values (Demongeot et al., 2025)

In addition to documenting crop diversity–stability patterns, understanding the underlying mechanisms is critical to make crop diversity a lever of farm climate-change adaptation. Two main mechanisms stand out in both natural and managed ecosystems. A selection effect occurs because diverse systems are more likely to comprise crops with intrinsically low yield variability. If these crops occupy a large share of cropland, they can drive greater stability of the whole farm portoflio (Barot et al., 2017). A complementarity effect arises when crops differ in their responses to environmental stresses, such that fluctuations in individual performances partly compensate each other through time. This is the principle of the "insurance effect" of biodiversity (Doak et al., 1998; Gross et al., 2014; Ives and Carpenter, 2007; Loreau and de Mazancourt, 2008; Tilman et al., 1998). While these mechanisms remain debated in ecology, they are still seldom examined in agroecosystems (but see Mahaut et al., 2021 at the national level and (Egli, Mehrabi, et al., 2021 at farm level).

In this study, we use a unique five-year monitoring program involving smallholder farms in Senegal to assess if, and how crop diversity at both the species and varietal levels contribute to stabilizing farms' total yields.

2. Material & Method

2.1 Study site

Our study was conducted in Senegal, in three villages (Sob, Ngayokhem and Diohine) of the "old peanut basin" (Delaunay et al., 2018, 2013) (Figure 1.a). The area lies within the Sudano-Sahelian zone characterized by a semi-arid climate with a long dry season (November–June) and a short rainy season (July to October) during which most agricultural activities occur (Nicholson, 2013). The region has experienced high rainfall variability, with a 30-year drought (Faye et al., 2020) followed by partial recovery (Lalou et al., 2019; Masse et al., 2018). Current annual rainfall averages 590 mm yr^{-1} (Faye et al., 2020) and temperatures varies between 24 and 30°C during the year. Soils are predominantly sandy (>95%), with low fertility and limited water retention capacity. Despite low topographic heterogeneity, hydromorphic sandy-clay soils (5–10% clay) with higher water retention capacity and fertility characterize inter-dune and lowland areas (Lericollais, 1999) .

In this agro-silvo-pastoral zone, the landscape is composed of agricultural fields punctuated with the multipurpose leguminous tree *Faidherbia albida* (Figure 1.a). Farmers in the area, predominantly from the Serer ethnolinguistic group, are smallholders (Masse et al., 2018) who mostly relies on livestock rearing and rain-fed agriculture to cultivate pearl millet (*Cenchrus americanus* (L.) Morrone syn. *Pennisetum glaucum* (L.) R. Br.), sorghum (*Sorghum bicolor* (L.) Moench), peanut (*Arachis hypogea* (L.)), cowpea (*Vigna unguiculata* (L.) Walp.) and roselle (*Hibiscus sabdariffa* (L.)). In one of the study villages, the cultivation of watermelon (*Citrullus lanatus* (Thunb.)) has emerged around the 2000'

(Masse et al., 2018). Even though most households maintain a garden, we focused our study on field crops. Crop fields are rotated from year to the next. Fallows have nearly vanished under increasing demographic pressure (Delaunay et al., 2018; Lericollais, 1999). Soil fertility remains a major limiting factor to agricultural productivity in the region (Muller et al., 2017) and application of mineral fertilizer remain minimal (Tounkara et al., 2020). Nutrient hotspots exist naturally in the vicinity of the leguminous tree *F. albida* or termite nests (Félix et al., 2018), and farmers apply livestock manure but mainly in homefields. Pesticides and irrigation water and used only on watermelon (Diatte et al., 2025). Cultivation is largely manual (hoes, sickles) or animal-drawn (seeders, plows, cultivators, mostly horse-powered) and the workforce labor is familial (Masse et al., 2018).

2.2 Data collection and preparation

Every year from 2020 to 2024, we surveyed 33 farms and monitored all their fields, recording the production of every crop species and variety. We worked with 13 farmers in Sob, 13 in Ngayokhem, and 7 in Diohine, cultivating a total of 137-143 fields depending on the year. Using data from a previous project (ESCAPE, Sultan, Lalou, Oumarou, et al., 2015), we selected farms along a gradient of crop species diversity, from low (one to two crops) to high (four to six crops). In addition, we obtained daily temperature and precipitation data from the Faidherbia-Flux experimental station located in Sob (Roupsard et al., 2019)

Farm surveys

To better understand how the socio-economic status of each farm relates to the crop diversity cultivated, we collected, in 2020, data on the age, caste, education level and non-agricultural activities of each households' head. Annually from 2020 to 2024, we also collected data on farms' assets, including the type and number of tools own (hoe, plough, seeder), draft animals (donkey or horse) and livestock raised (goat, cattle, sheep).

Field surveys

During annual field surveys, we listed crops at both species and varietal levels and measured their cultivated area, data necessary to calculate crop diversity and crop yield.

During annual field surveys, we measured the area of every field actively cultivated by the 33 farmers using a handheld GPS (Garmin eTrex 30), a method widely recommended for its accuracy and efficiency (Carletto et al., 2016; FAO, 2017). During field visits, we also recorded crop species and variety, as named by farmers, and their spatial arrangement within fields (Figure 2). Crops in monoculture (45.3% of fields surveyed over the five years) were attributed the full area of the field. Allocating area to crops was more complex in the remaining fields (54.7% of all fields surveyed over the five years), where multiple species and varieties were sown together (local intercropping patterns are detailed in SM1).

Two main approaches can be used to estimate area occupied by each crop and variety in intercropped fields: (i) the allocated area, which is the physical fraction of the field occupied by a given crop (Fermont and Benson, 2011) and (ii) the imputed area, which is the area that a given variety would occupy if grown in monoculture (FAO, 1982; U.C. Sud et al., 2016). We adopted the imputed area approach because the resulting yield values per crop were more consistent with the literature (Appendix A).

To calculate imputed area, we first measured sowing density of each crop in monoculture and intercropped fields over three years (2020-2022). Sowing density is a parameter widely recognized for its reliability based on actual field observation leading to a greater precision (FAO, 2017, 1982). In each field, we measured the distances (in meters) between four consecutive rows and between four consecutive hills within a row. For each variety *i*, sowing density (hills. ha^{-1}) was calculated as:

$$Sowing\ density_{\ i} = 10{,}000 \times \frac{Mean\ inter-hills\ spacing}{Mean\ inter-row\ spacing}$$

For roselle, which is typically grown along field borders, we only measured the distance between hills. Sowing density was then estimated as the number of hills (field perimeter divided by mean inter-hill distance) relative to the total field area. Because sowing density did not vary among varieties within a species, we calculated mean densities for each species in both monoculture and specific intercropping patterns. The only exception was cereals, where early- and late-flowering varieties were analyzed separately due to their distinct cropping association patterns (SM2).

The imputed area of variety *i* in field *j* was calculated as:

$$Imputed\ Area_{\ i} = \frac{Sowing\ density_{intercrop\ i}}{Sowing\ density_{monoculture\ i}} \times Surface_{\ j}$$

When multiple varieties of the same species were cultivated in the same field, the imputed area was equally divided among varieties. Finally, for each year, we derived the total imputed cultivated area of each farm by summing the imputed area of each variety cultivated by this farm.

Based on the list of crops per field and imputed areas, we derived on-farm crop diversity for two levels: Sp – the total number of species and SpV, the total number of varieties across species, and not to the number of varieties per species. We used two diversity metrics. First, the richness, which is the count of Sp or SpV, respectively, per farm. Second, the effective diversity ($e^{H'}$), which is the exponential of the Shannon index (H′). Shannon weights the number of Sp and SpV, respectively, by the proportion of cultivated area (see below). The effective diversity provides the number of equally abundant Sp or SpV required to obtain the observed H' value. To align with our calculations of yield temporal stability (see section below), we averaged, for each farm, the annual richness and effective Sp and SpV diversity values across the five years. All the computations were done using the "vegan" package in R version 4.3.2 (Oksanen et al., 2025).

Production surveys

For each crop cultivated on a farm, we computed yield as the total production divided by the total cultivated area for that crop. To do that, each year from 2020 to 2024, we weighted the grain biomass of each variety of each crop species for all 33 farms. But measuring yield of every crop Sp and SpV in a system represent a methodological challenge. We carried out the measurements when the total harvest was brought back to the village, thereby aggregating the production across all the fields of a given farm (Figure 1. b, c, d, e). Because harvest practices differ across crops (fresh versus dry, type of container, single versus sequential harvests; Table 1), we used crop-specific methods to estimate production.

For pearl millet, sorghum and watermelon, we applied the FAO harvest-unit sampling method (FAO, 2017; Poate, 1988). For each variety of these three species, the method consists of counting the total number of harvest units (Table 1), weighing a subsample of units, and multiplying the mean unit weight by the total number of units to obtain farm-level production. As sorghum is harvested fresh, we weighed a subsample of fresh plants and re-weighed them after drying to derive a fresh-to-dry conversion ratio, which we then applied to total fresh yield to estimate dry biomass.

For cowpea, peanut and roselle, we weighed all harvest units and summed the weights to obtain total production. Cowpea is also harvested and consumed fresh continuously in September (first crop to be harvested), so we could not divert a subsample for drying. Instead, we weighed each fresh harvest before consumption and summed all measurements over the season. We performed all weightings using a suspended scale.

Crop species	**Unit**	**Weighted units**	**Method to estimate production (Kg)**
Pearl millet	Dry millet bundle	20	FAO harvest-unit sampling (Total bundles × mean weight of 20 bundles)
Sorghum	Fresh sorghum basin	20	FAO harvest-unit sampling
Peanut	Dry peanut 50-kg sacks	All	Sum of all sacks' weights
Roselle	Dried roselle flowers in 50-kg sacks	All	Sum of all sacks' weights
Cowpea	Fresh cowpea sacks or basins	All	Sum of all unit weighted (Note: harvested continuously; weighed at each collection)
Watermelon	Individual fruit	20	FAO harvest-unit sampling

Table 1. Crop production estimation. For each crop species, we detail the harvested form, the way it is conditioned by farmers and the method used to estimate their production.

Following Renard & Tilman (2019), we converted the biomass produced by crops (in kg) into calories to allow the aggregation of production across crops with different energy densities. To do this, we multiplied the production of each of its crops by commodity-specific kcal conversion factors from the

USDA's Nutrient Database (USDA, 2019) to get the kcal production of each crop. As no variety-specific conversion factors exist, we applied each species' factor uniformly across all its varieties.

Finally, for each farm, we calculated annual total caloric yield (in megacalorie [e.g., one million calories] per ha; Mcal ha^{-1}) by summing the annual production across all Sp or SpV, and then dividing by its respective total imputed cultivated area.

2.3 Data analyses

We evaluated the links between socio-economic status of each farm and its level of Sp and SpV diversity, respectively. For binary predictors (i.e., non-agricultural activity, education of household head, see Appendix B for details), we used either Student's *t*-tests (when assumptions of normality and homoscedasticity were met) or Mann–Whitney U tests (when they were not). For categorial variables (i.e., village, caste), we used either ANOVA (parametric test) or Kruskal–Wallis test (non-parametric). For continuous quantitative indicators, we fitted simple linear models between effective Sp diversity and each indicator.

For each farm, we estimated the temporal stability of caloric yield (S) using the ratio of the mean annual caloric yield (μ) over its temporal standard deviation (σ) across the five years of our survey (Tilman et al. 1998). To examine the relationships between farm-level crop diversity and total caloric yield stability, we ran linear regression models including the two diversity metrics (richness and effective diversity) and for both Sp and SpV levels. To ensure the normality of residuals, we log-transformed S, μ, and σ. Because higher stability can arise from yield enhancement (higher μ) or risk reduction (lower σ), we further fitted separate linear models relating each component (μ and σ) to the crop diversity indices to investigate whether diversity primarily promotes productivity, reduces variability, or both.

We then tested processes underlying the crop diversity-stability relationship. To evaluate the role of the selection effect, we first compared the temporal caloric yield stability of among individual Sp and SpV cultivated per farm, respectively, using Kruskal-Wallis tests, followed by post-hoc pairwise Wilcoxon tests with Benjamini-Hochberg correction. Individual stability could not be assessed for Sp or SpV cultivated only one year by a single farm (n=29 and 44 respectively). Second, to identify Sp or SpV contributing most to stabilizing total farm yield, we calculated farms' stability (S') dropping each Sp or SpV *i* at a time, over the entire time period (Renard & Tilman 2019). The log response ratio of stability between the exclusion scenario and the baseline ($-\log_2(S'/S)$) indicates whether *i* has a stabilizing (negative log response ratio) or a destabilizing effect (positive log response ratio). Stability was calculated on farms with at least three years of yield data (mostly when farmers cultivate more than just pearl millet). We statistically compared the log response ratios to zero using a one-sample Wilcoxon signed-rank test.

We then evaluated the role of the insurance effect in stabilizing farm yield. For each farm, we evaluated whether individual Sp and SpV, respectively, fluctuated synchronously or asynchronously through time using the index developed by Loreau & de Mazancourt, (2008):

$$asynchrony = 1 - \ synchony = 1 - \Phi = 1 - \frac{\sigma^2}{\left(\sum_{i=1}^{N} \sigma_i\right)^2}$$

where σ^2 is the variance of total farm caloric yield (million kcal ha^{-1}), and σ_i is the standard deviation of caloric yield for each species or variety *i*. Values range from 0 (perfect synchrony among Sp or SpV) to 1 (perfect asynchrony). Computations were done in R (version 4.3.2) using the "Codyn" package (Hallett et al., 2016). To calculate asynchrony, data needed to comply to two conditions: (i) farms must grow at least two Sp or SpV per year and (ii) each Sp or SpV must be cultivated by the same farm at least two years over the study period. Observations failing either condition were excluded. Finally, we tested the relationships between farm yield asynchrony and farm diversity and between farm yield asynchrony and total farm yield stability using linear regression models. Because most farms grew only one or two varieties of each species, we visually evaluated the potential asynchronous dynamics between varieties of the species.

We used annual climatic data to calculate the total amount of rainfall (in mm) and the mean number of days between the first three rainfall events (>10 mm) of the season. The latter metric was used as an indicator of early-season dry spells, a particularly damaging event at the beginning of the growing season when seeds are sown or seedlings emerge (Marteau et al., 2011; McCord et al., 2015).

3 Results

3.1. Crop diversity in the area

We observed substantial variation in the total imputed cultivated area across the 33 farms, ranging from 0.47 to 4.35 ha (mean ± SD; 2.26 ± 1.27 ha), with no significant difference among villages (ANOVA: $P = 0.90$).

Across all farms, six Sp and 18 SpV were grown (Figure 3). Pearl millet dominated land use, accounting on average for 41.3% of the total cultivated area per year (± 5.5%). Farmers grew three pearl millet varieties—two early-flowering (varieties names *Souna* and *Guiss*) and one late-flowering (*Sanio*). All farmers cultivated at least one early-flowering variety, sometimes mixed with *Sanio*, but never combined two early-flowering varieties, nor cultivated *Sanio* alone. We recorded four varieties of peanut (named *Fouré, Yeger, Essaie-moi* and *Lao*) and five varieties of cowpea (*Ngagne, Mbilix, Sodeva, Melex, Fandan*). Peanut and cowpea accounted on average for 24.3% (± 3.2%) and 23.3% (± 2.0%) of the imputed cultivated area, respectively. Minor crops in terms of cultivated area included a single variety of watermelon (*Greybelle,* 4.8% ± 2.6%), three varieties of roselle (*Vinto, Fandan, Rouge clair*;

accounting together for 3.7% ± 0.5% of cultivated land area), and two sorghum varieties (*Patch*, *Sorgho*; 2.5% ± 0.2% together). Except for water-melon, varieties are landraces rather than improve cultivar.

Farm-level Sp richness averaged 3.77 (± 1.37), while SpV richness averaged 5.03 (± 2.24). Most farmers cultivated a single variety per species (mean varietal richness: 1.16–1.38 for millet, peanut, and cowpea), except for roselle (1.85 ± 0.30). Farmers cultivated only one sorghum and watermelon variety each year. Effective Sp diversity average 2.96 (± 1.05) and effective SpV diversity 3.47 (± 1.46). The three villages did not significantly differ in either richness (Kruskal-Wallis test, Sp: P=0.19; SpV: P=0.69) nor effective diversity (Kruskal-Wallis test, Sp: $P = 0.22$; SpV: $P = 0.41$).

We found that farms with higher effective Sp diversity cultivated significantly larger areas ($F_{1,31} = 37.66$, $R^2 = 0.54$, $P < 0.001$), possessed greater agricultural capital, including more animal-drawn tools (T-test: $P = 0.016$), more draft animals (ANOVA: $P = 0.02$), and livestock (T-test: $P = 0.02$). Conversely, less diversified farms were more likely to engage in non-agricultural activities (Mann–Whitney U test: $P = 0.004$) and predominantly belonged to the *griot* caste, a hereditary group traditionally dedicated to arts and oral history rather than land cultivation (ANOVA: $P < 0.001$). We found no significant correlation between effective Sp diversity with household head age ($F_{1,31} = 0.66$, $R^2 = 0.02$, P = 0.42), educational level (T-test: $P = 0.22$), or labor ($F_{1,31} = 1.26$, $R^2 = 0.04$, P = 0.27).

3.2 Greater crop diversity leads to enhanced farm yield stability

We found a positive and significant correlation between farm's total temporal yield stability and both effective Sp and SpV diversity (P < 0.05 respectively; Figure 4.a and Appendix C). For example, farmers cultivating fewer than three species had a mean stability of 2.66 (± 1.01), whereas those cultivating more than five species exhibited a nearly twofold higher stability (4.48 ± 1.91). We then examined how diversity related to the two components of yield stability, namely mean yield and its standard deviation. Higher effective diversity (Sp and SpV) was significantly associated with lower inter-annual standard deviation of yield ($P < 0.05$, Figure 4.b and Appendix C) but was not related to mean yield (Figure 4.c). Analyses using species richness showed similar results (Appendix C).

3.3 Contributions of individual species and varieties to farm's total yield stability

Yield stability differed significant among crop Sp (Kruskal–Wallis test, $P = 0.005$) and among SpV (Kruskal–Wallis test, $P = 0.001$). Pearl millet, roselle, and peanut showed higher yield stability compared to cowpea (post hoc pairwise Wilcoxon tests; Figure 5.a), and analyses conducted at the varietal level showed similar patterns. In contrast, when a species included more than one variety, we found no significant differences in yield stability among varieties (Figure 5.b).

The log-response ratio showed that pearl millet contributed significantly more than other crops to the overall farm-level yield stability ($P < 0.01$; Figure 6.a). We found no significant differences between varieties individual contribution to farm's yield stability (Figure 6.b).

3.4 Asynchrony in crop's individual yield drives the crop diversity-stability relationship

Asynchrony between yield of individual Sp and SpV was significantly greater on farms cultivating higher effective diversity. Asynchrony was more strongly associated with effective SpV diversity ($F_{1,27}$ = 14.01, R^2 = 0.34, P < 0.001) compared to effective Sp diversity (Figure 7.a ; $F_{1,27}$ = 9.41, R^2 = 0.26, P = 0.0049). Farm-level yield stability was positively correlated with yield asynchrony both among Sp (Figure 7.b ; $F_{1,27}$ = 10.48, R^2 = 0.28, P = 0.0032) and among SpV ($F_{1,27}$ = 14.35, R^2 = 0.35, P < 0.001).

The five-year study period was marked by high climatic variability, featuring both droughts (notably dry spells) and floods (Figure 8.a). Visual inspection of annual SpV yield fluctuations revealed marked asynchrony, especially for pearl millet and sorghum (Figure 8.b, c). For pearl millet, yield of the late-flowering *Sanio* fluctuated inversely with yields of early-flowering *Souna* and *Guiss* varieties. This pattern was particularly clear in 2022, characterized by the longest dry spells at the beginning of the season, followed by substantial late rainfall and flooding. In 2023, the climatic sequence was reverse (flooding and then drought) and varietal yield responses switched accordingly (Figure 9). For sorghum, the *Patch* and *Sorgho* varieties also appeared to show contrasting yield trends, particularly during 2020 and 2022. By contrast, we did not observe clear asynchronous dynamics among varieties of peanut, cowpea, or roselle.

4 Discussion

We found that higher crop diversity at both species and varietal levels enhances yield stability of smallholder farms in semi-arid conditions. We provide evidence that the crop diversity–stability relationship is driven by two mechanisms with distinct contributions from different levels of diversity: the high stability of the dominant crop species; pearl millet and the asynchronous yield fluctuations among crops, a dynamic that appears slightly more pronounced at SpV levels. This farm scale work not only contributes to current efforts demonstrating the consistency of the diversity–stability relationship across scales, but also provides new insights into how diversification at both Sp and SpV levels can support food security under conditions of high climatic variability and unpredictability.

We show that, within farms, the cultivation of greater crop diversity enhances total caloric yield stability across the five years of our monitoring program. Despite the relatively low number of farmers involved in our study—constrained by the resources needed to collect annual data on every field and crop—our results provide robust, field-based evidence of the contribution of agrobiodiversity to yield stability at the farm level (Egli et al., 2021a; Menesch et al., 2023).

Our main contribution to the active research on crop diversity-stability relationship lies in simultaneously assessing the effects of crop Sp and SpV. This way, we offer a more accurate reflection of smallholders' management of crop diversity compared to either experiments under controlled conditions or large-scale observational studies. We found that both Sp and SpV had positive effects on yield stability, with Sp diversity slightly outweighing the effect of SpV diversity. The lack of more

pronounced differences between levels of diversity contrasts with results reported by Prieto et al. (2015). In fact, in our study system, farmers grow only few varieties per species, resulting in only minor variation in both crop Sp and SpV diversity levels. But findings may differ in biodiversity hotspots where farmers traditionally maintain multiple varieties per species, as is the case in Africa for sorghum (Barnaud et al., 2007), Peru for potato (Haan et al., 2010), or in India for wheat and rice (Gotor et al., 2021). Presenting the third study, to our knowledge, specifically addressing the respective effects of both levels of crop diversity on yield stability, our findings highlight the need for future research that adopts a more holistic, field-grounded approach to agrobiodiversity.

Our results also show that stability gains from greater crop diversity, at both species and varietal levels within farms, stem from reduced yield variability (i.e., standard deviation), with no impact on mean yields. This may seem surprising, given that a study in the same agroecosystem in Senegal found that within-field diversity—pearl millet varietal mixtures—significantly increases yields (Cissé et al., 2023). However, the number of components in a mixture can strongly influence the mixture's yield advantage (Beillouin et al., 2021). Whereas (Cissé et al., 2023) investigated four-component mixtures, the varietal mixtures studied here were almost entirely composed of only two components. Moreover, mechanisms leading to greater stability, e.g., the selection and insurance effects, can operate when crop diversity is maintained across fields in monocultures, increases in mean yield mainly result from mechanisms operating within fields (e.g., facilitation, differential resource use) when crops directly interact. Because we did not measure yield at the field level, we were unable to detect the potential effects of intercropping or mixture on mean yield. The literature frequently reports reductions in yield variability from country to field scales (e.g., Renard & Tilman, 2019; Su et al., 2025), yet the effects of agrobiodiversity on mean yields remain variable and likely context- or practice-dependent (Beillouin et al., 2021, 2019). These two outcomes are rarely studied jointly, making it difficult to identify the conditions under which crop diversity supports multiple outcomes simultaneously. This is particularly important in smallholder farming contexts, where closing yield gaps and enhancing stability can both significantly reduce hunger (FAO, 2025).

Our study also contributes to identify mechanisms underlying the crop diversity-stability at farm scale. Consistent with national-scale findings (Mahaut et al., 2021), our results indicate that the crop diversity–stability relationship arises from two complementary mechanisms: individual crop stability and yield asynchrony among crops and varieties.

In our study agroecosystem, the crop with the highest individual yield stability was pearl millet. Because it is also the species occupying the largest share of cropland across farmers, its performance largely influences the total stability of farmers' crop portfolios, supporting a selection effect (Barot et al., 2017). However, relying solely on this mechanism may not represent a sustainable pathway. Pearl millet—a native, drought-tolerant African crop (Shrestha et al., 2023) with strong socio-cultural value (Cobelli, 2018; Labeyrie et al., 2023; Lericollais, 1999; Pélissier, 1953)—is approaching the limits of its climatic

suitability. Projections indicate that some regions are becoming unsuitable for its cultivation (Rhoné et al., 2020), and abandonment has already begun in certain areas (Olodo et al., 2020; Sall et al., 2025). Although farmers' crop management is dynamic, with frequent adoption and abandonment events (Acevedo et al., 2020), how these changes in crop portfolio composition and diversity affect mean yields and temporal stability remains unknown. When new crops are adopted, previous research highlight that farmers often choose horticultural species that are not always well-adapted to local environmental conditions and may compete for scarce water resources under future climatic conditions (Labeyrie et al., 2021). Crucially, the stabilizing effect of these new crops is rarely assessed. Our results suggest that, despite fertilization and irrigation, the recently introduced watermelon (Masse et al., 2018; Muller et al., 2017) does not appear to contribute to crop portfolio stability—though our sample size is limited—even if it may support food security by generating household income.

We found that the asynchronous fluctuations of individual crop yields, which appear slightly more pronounced at the varietal level, also plays a role in stabilizing the total yield of diversified farms. The role of the insurance effect of biodiversity has been also recognized in previous studies in both natural (Hector et al., 2010; Schnabel et al., 2021; Xu et al., 2021) and managed ecosystems (Stefan et al., 2024; Su et al., 2023). Although there is growing recognition that this mechanism operate through differences in functional traits among organisms (de Bello et al., 2021), the specific traits or trait combinations involved remain to be identified. In agroecosystems asynchrony has been attributed to species' growth cycles (e.g., flowering dates in millet; De Rouw & Winkel, 1998), intraspecific trait dissimilarity (e.g., plant or ear height; Su et al., 2025), or differential responses to species-specific interactions (Yang et al., 2026). Phenology may be a key trait underlying asynchronous dynamics in our study system. We observed visible asynchrony between early-flowering (*Guiss*, *Souna*: 85–95 days) and late-flowering (*Sanio*: 110–140 days) pearl millet varieties, especially during years with severe early dry spells (in 2022), when late-flowering varieties performed better due to a longer growth window. The duration of crop cycles is indeed a primary selection criterion for farmers in this region facing climate change (Ruggieri et al., 2021), an adaptation that ensures sensitive phenological stages avoid periods of high climatic risk. However, asynchrony between yields of sorghum varieties, both of which are late flowering, suggests that other traits are also involved and need to be identified.

Identifying which crops underlie the selection and insurance effects of agrobiodiversity are key to translating research into actionable recommendations for farmers. At present, only a small number of farmers in our study area combine short- and long-cycle millet varieties (3-7 farmers per year), and none cultivate both sorghum varieties simultaneously. This indicates that asynchrony may represent an underutilised strategy to stabilize yields in our study system and that varietal mixtures of pearl millet varieties could enhance stability not only through temporal complementarity but also via yield increases (Cissé et al., 2023). Supporting larger uptake of such practice could be feasible on the ground, as knowledge and seeds are already available locally, and farmers cultivating crop diversity already have

the financial and material capital. Although enhancing cultivated diversity appears to be a relevant lever for improving yield stability, less diversified farms primarily rely on off-farm income sources and general recommendations to increase diversity may be less relevant.

Several limitations should be acknowledged. Although we did not have sufficient data to statistically test the effect of fertilization, the limited differences in local management practices suggest that manure fertilization is unlikely to have had a significant impact. In addition, existing studies suggest that the stabilizing effect of fertilization is negligible compared to that of cultivated diversity (Doncieux, 2023; Menesch et al., 2023; Renard and Tilman, 2019). We further note that our measurements are based on grain biomass yields and therefore exclude fodder production, which can play an important role in household economies, particularly for sorghum, peanut, and certain cowpea varieties (Cobelli, 2018; Labeyrie et al., 2023; Ruggieri et al., 2021).

5 Conclusion

In the course of only five years, our study site faced two years with dry spells and floods. Such climatic variability and unpredictability from one year to the next illustrate the type of risk that farmers are increasingly facing and highlight that adaptation measures designed to cope with a single or few perturbation types are of limited value. In addition to demonstrating that cultivating a diversity of crop species and varieties enhance yield temporal stability in this complex climatic context, we provide new insights about crops and traits to guide farmers to enhance their yield stability without necessarily large change additional capital.

Fundings

Research leading to this contribution was supported by core funding from IRD (Institut de recherche pour le dévelopement), the French National Research Agency (ANR) under the 'Programme d'Investissements d'Avenir' (reference 17-MPGA-0004) as well as the European Union's Horizon Europe research and innovation program (Grant agreement No 101041069 – ARISER). This work also received financial support from the Défi Clé Octaave, funded by the Occitanie Region, France.

Declaration of Competing Interest

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

Data Availability

The processed dataset supporting the findings of this study will be deposited in the CIRAD Dataverse repository (https://dataverse.cirad.fr/) upon acceptance of the article.

Acknowledgments

We warmly thank the farmers of Sob, Diohine, and Ngayokhème for their long-term commitment to this study. Year after year, they have welcomed us with hospitality, patiently answering our questions, allowing us to visit their fields, and weighing their entire harvests. We are particularly grateful to the Niakhar Health and Demographic Surveillance System (HDSS) and the IRD Niakhar team for making this work possible, facilitating field organization, and sharing geographical data. We also extend our sincere thanks to the "Faidherbia-Flux" platform (https://lped.info/wikiObsSN/?Faidherbia-Flux), and especially to Olivier Roupsard, for sharing climatic data. Finally, we thank Océane Cobelli for her assistance in cleaning the initial datasets.

CRediT authorship contribution statement

Ewen Menguy: Methodology, Formal Analysis, Investigation, Data Curation, Writing - Original Draft, Visualization. **Adeline Barnaud**: Conceptualization, Methodology, Writing - Review & Editing, Supervision, Project administration. **Stéphanie M. Carrière**: Writing - Review & Editing. **Robert Diatte**: Investigation, Data curation. **Abdou Ngom**: Investigation. **Saidou N. Sall**: Writing - Review & Editing. **Paul Sene**: Investigation. **Vanesse Labeyrie**: Validation, Writing - Review & Editing, Funding acquisition. **Cécile Berthouly-Salazar**: Conceptualization, Methodology, Validation, Writing - Review & Editing, Supervision, Project administration. **Delphine Renard**: Conceptualization, Methodology, Validation, Writing - Review & Editing, Supervision, Project administration, Funding acquisition

Appendices

Appendix A

Crop mean yields (quintals/ha) estimated from field data (all farms, all years) using allocated versus imputed area approaches. For comparison, we include national FAOSTAT averages (1961–2024) and literature references as close as possible to our study site (in Niakhar, central Senegal). Comparison shows that yield estimates for cowpea and roselle were overestimated when using the allocated area approach, while consistent with values from the literature when using the imputed area approach. Given the greater coherence of the imputed approach, all subsequent analyses in this article are based exclusively on this method

Yield estimation (qt ha^{-1})	**Allocated approach**	**Imputed approach**	**FAO Stat (1961–2024)**	**Literature values**
Pearl millet	15.43 ± 2.19	14.52 ± 3.25	6.50 ± 2.01	**10.05** (National data, Fatick District; Vieira Junior et al., 2023); **1.00–19.37** (Farmer fields, Central Senegal; Kouakou et al., 2015) **2.31–2.97** (On-farm trials, Central Senegal, Cissé et al., 2023)
Peanut	6.08 ± 0.76	5.72 ± 0.55	8.88 ± 2.39	**6.25** (Farmer fields, Niakhar; Djiba et al., 2025)
Cowpea	13.24 ± 3.93	1.52 ± 1.02	3.71 ± 1.52	**4.19** (On-station trials, Bambey Research Station; A. Faye et al., 2024); **0.35–1.00** (Median yields, farmer fields, Central Senegal; Beye et al., 2022; Obour et al., 2024)
Watermelon	356.31 ± 41.56	355.72 ± 42.24	147.37 ± 26.76	**200-450** (ISRA, Beniest et al., 1987)
Sorghum	8.56 ± 4.26	7.74 ± 6.48	8.96 ± 2.16	**5.3–12.11** (On-station trials, Bambey Research Station; Ndiaye et al., 2018))
Roselle	19.75 ± 8.07	4.15 ± 0.55	-	**2.5–5** (ISRA, Cisse et al., 2009)

452 **Appendix B**

453 Statistical tests applied to evaluate the relationship between farm effective species diversity and each
454 socioeconomic variables, selected according to variable type.

Variable	**Type**	**Statistical test used**
Village	Multi-category (Sob, Ngayokhem, Diohine)	Kruskal–Wallis test
Cultivated area (ha)	Continuous	Linear model
Household head age	Continuous	Linear model
Caste of household head age	Multi-category (Griot, royal, none)	ANOVA
Education of household head	Binary (None vs ≥ primary school)	Student's t-test
Available family labor (number)	Continuous	Linear model
Non-agricultural activity	Binary (yes/no)	Mann–Whitney U test
Livestock (goat, cattle or sheep)	Binary (≤1 vs >1 types)	Student's t-test
Draft animals (donkey or horse)	Multi-category (none / donkey or horse / both)	ANOVA
Draft tools (hoe, plow or seeder)	Binary (≤1 vs >1)	Student's t-test

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Appendix C

Linear regression results for farm stability (S = μ/σ; n=33 farms), its components - mean yield (μ) and yield variability (σ) - and asynchrony, tested against effective diversity and species richness for both Sp and SpV. Two distinct datasets were used to estimate species- and varietal-level asynchrony (n=29 farms respectively). Crop area for yield stability and all diversity metrics calculation are based on imputed area approach (see Materials and Methods for details).

Response variable	Indices	Sp/SpV	β ± SE	F (1, df)	R^2	P	Sig.
Yield Stability	Effective div.	Sp	0.18 ± 0.07	7.12 (1, 31)	0.19	0.012	*
		SpV	0.16 ± 0.07	5.46 (1, 31)	0.15	0.026	*
	Richness	Sp	0.15 ± 0.07	4.79 (1, 31)	0.13	0.036	*
		SpV	0.14 ± 0.07	3.86 (1, 31)	0.11	0.059	ns
Mean yield	Effective div.	Sp	-0.02 ± 0.07	0.07 (1, 31)	<0.01	0.79	ns
		SpV	-0.05 ± 0.07	0.45 (1, 31)	0.01	0.51	ns
	Richness	Sp	-0.05 ± 0.07	0.46 (1, 31)	0.01	0.50	ns
		SpV	-0.07 ± 0.07	1.14 (1, 31)	0.04	0.29	ns
Yield standard deviation	Effective div.	Sp	-0.20 ± 0.08	5.71 (1, 31)	0.16	0.023	*
		SpV	-0.21 ± 0.08	6.34 (1, 31)	0.17	0.017	*
	Richness	Sp	-0.20 ± 0.08	5.73 (1, 31)	0.16	0.023	*
		SpV	-0.21 ± 0.08	6.58 (1, 31)	0.18	0.015	*
Asynchrony Sp.	Effective div.	Sp	0.11 ± 0.04	9.41 (1, 27)	0.26	0.005	**
	Richness	Sp	0.10 ± 0.04	7.54 (1, 27)	0.22	0.011	*
Asynchrony SpV	Effective div.	SpV	0.15 ± 0.04	14.01 (1, 27)	0.34	<0.001	***
	Richness	SpV	0.15 ± 0.04	13.08 (1, 27)	0.33	0.001	**

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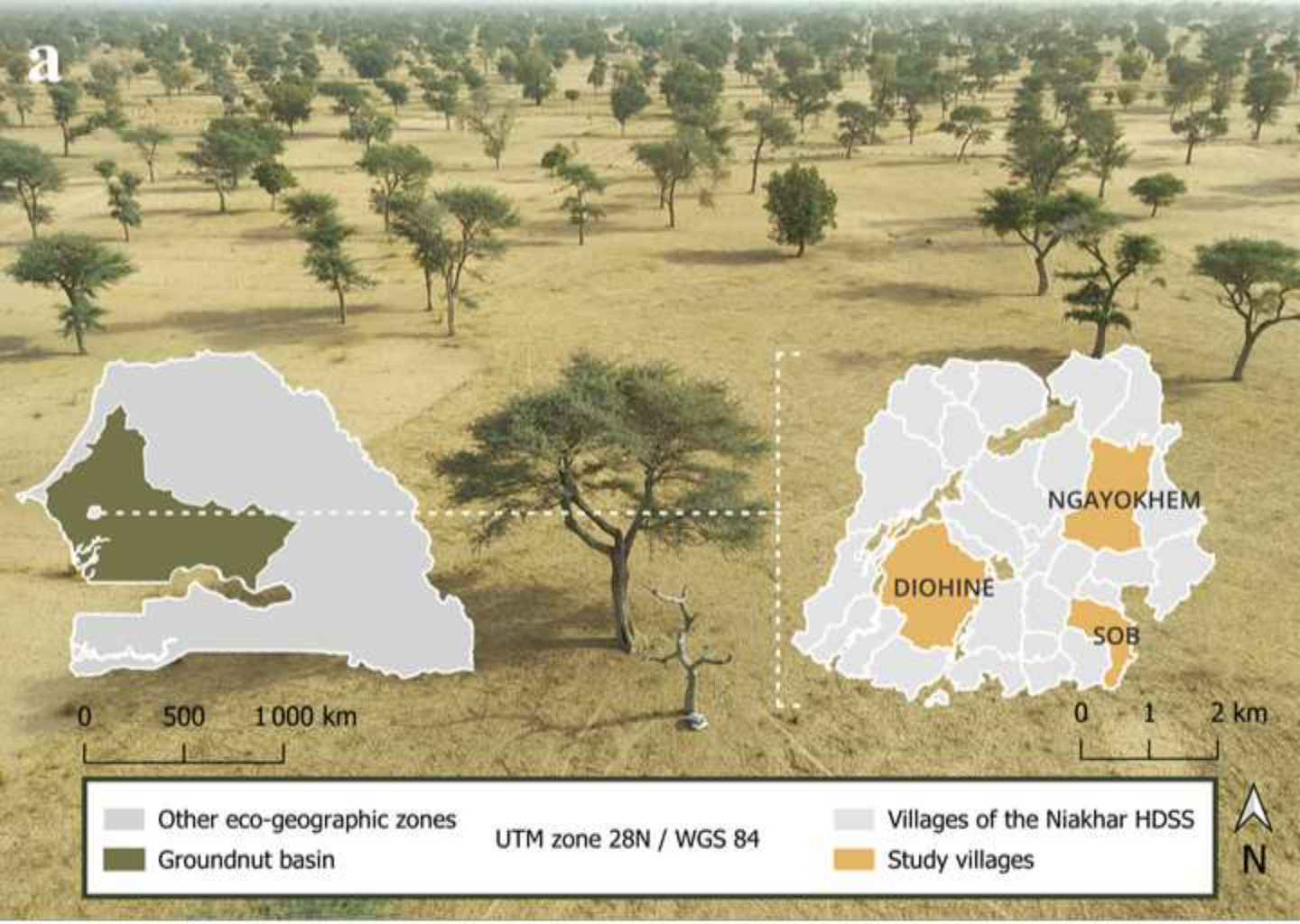
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a
NGAYOKHEM
DIOHINE
SOB
0 500 1 000 km
0 1 2 km
Other eco-geographic zones
Groundnut basin
UTM zone 28N / WGS 84
Villages of the Niakhar HDSS
Study villages
N

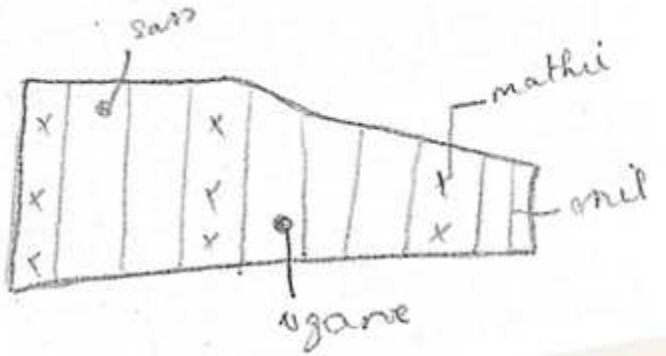

b

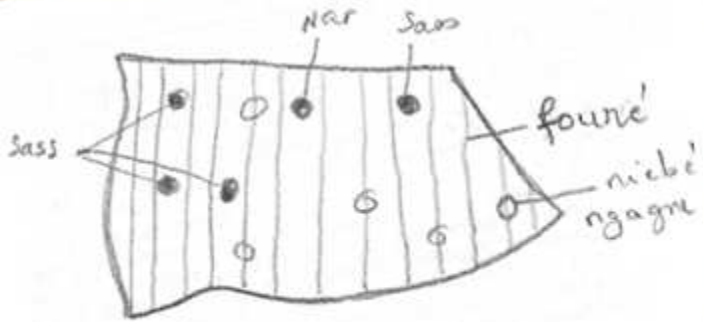

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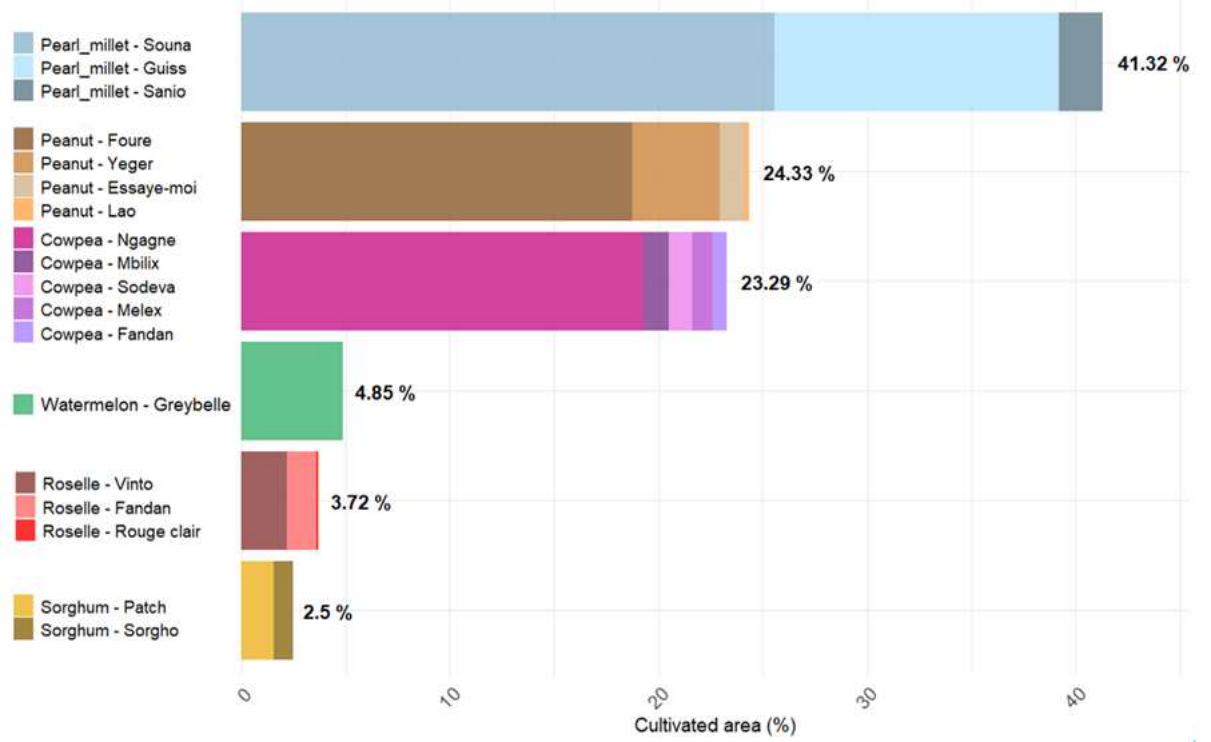

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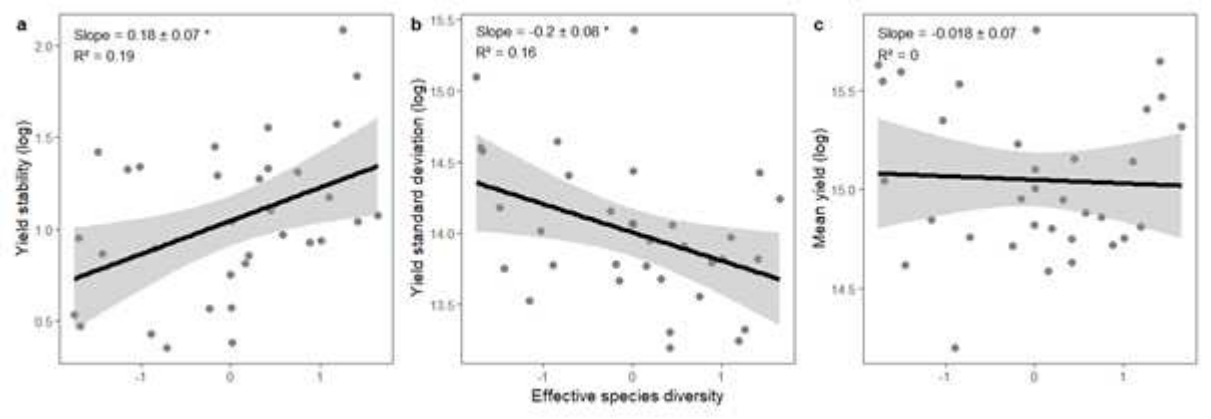


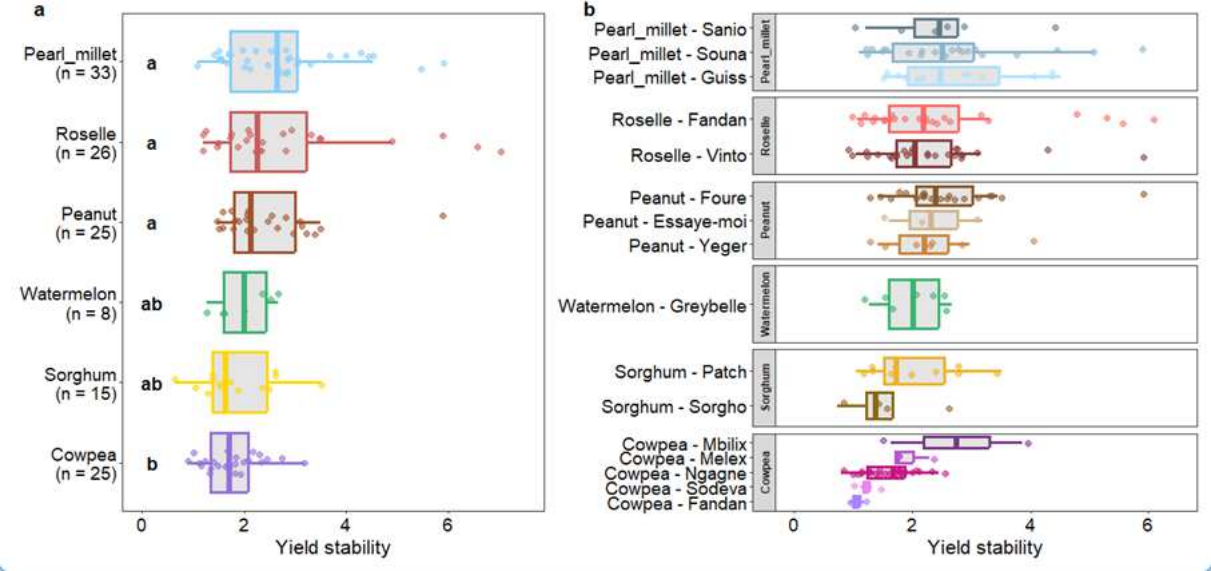

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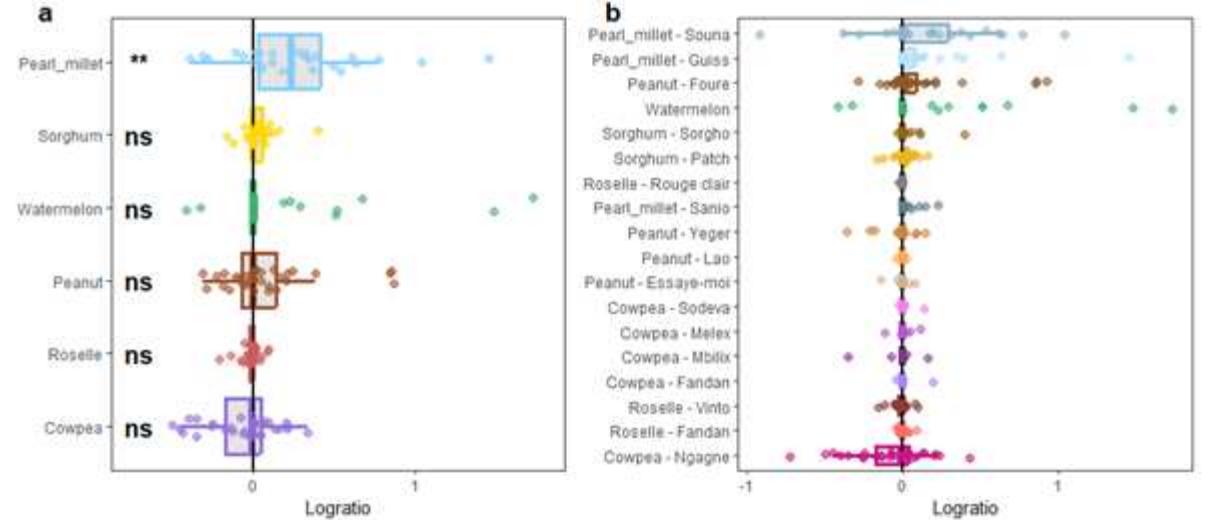

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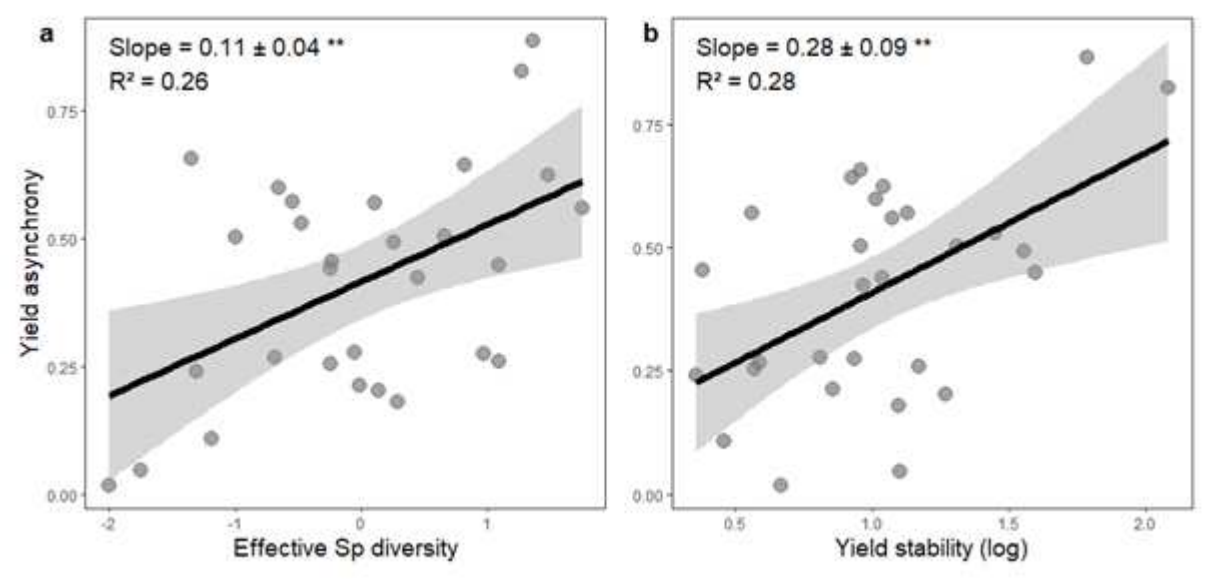


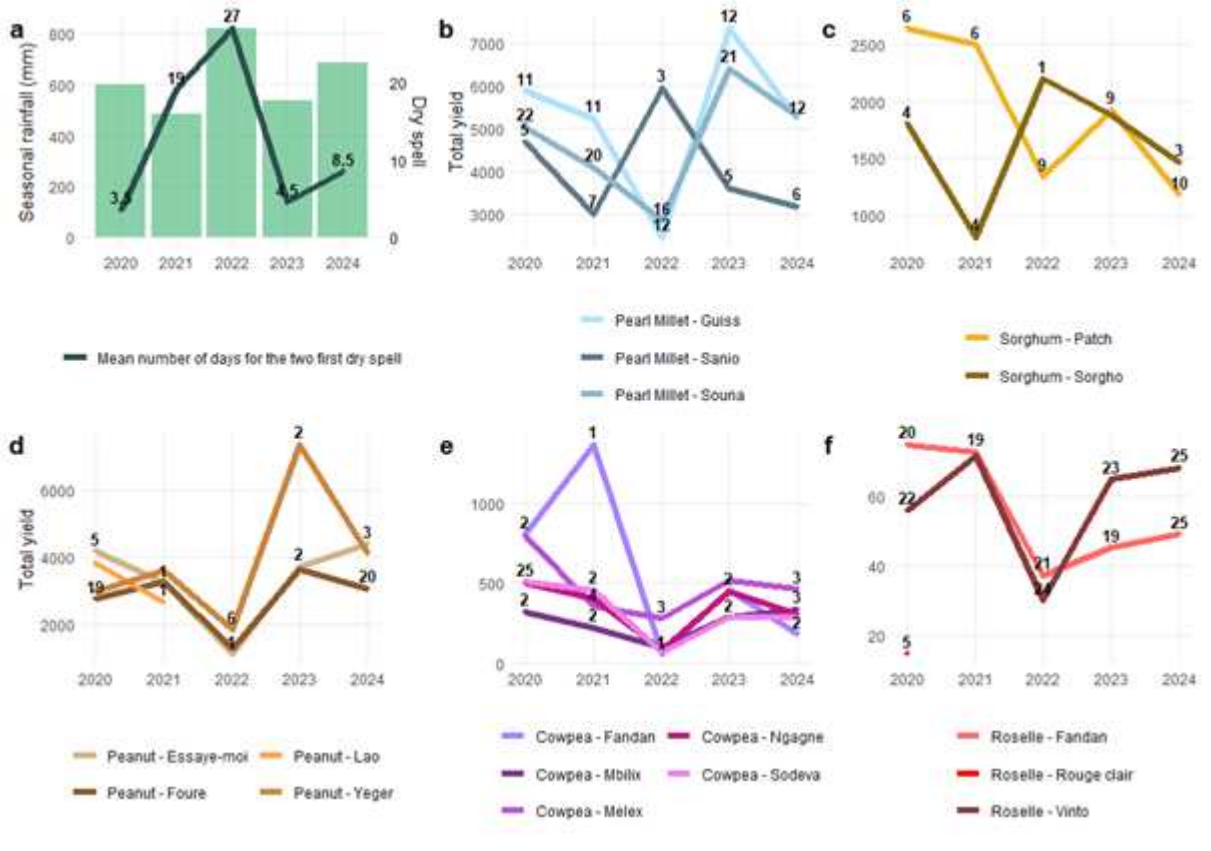

Pearl_millet - Souna
Pearl_millet - Guiss
Pearl_millet - Sanio
41.32 %
Peanut - Foure
Peanut - Yeger
Peanut - Essaye-moi
Peanut - Lao
24.33 %
Cowpea - Ngagne
Cowpea - Mbilix
Cowpea - Sodeva
Cowpea - Melex
Cowpea - Fandan
23.29 %
Watermelon - Greybelle
4.85 %
Roselle - Vinto
Roselle - Fandan
Roselle - Rouge clair
3.72 %
Sorghum - Patch
Sorghum - Sorgho
2.5 %
0
10
20
30
40
Cultivated area (%)

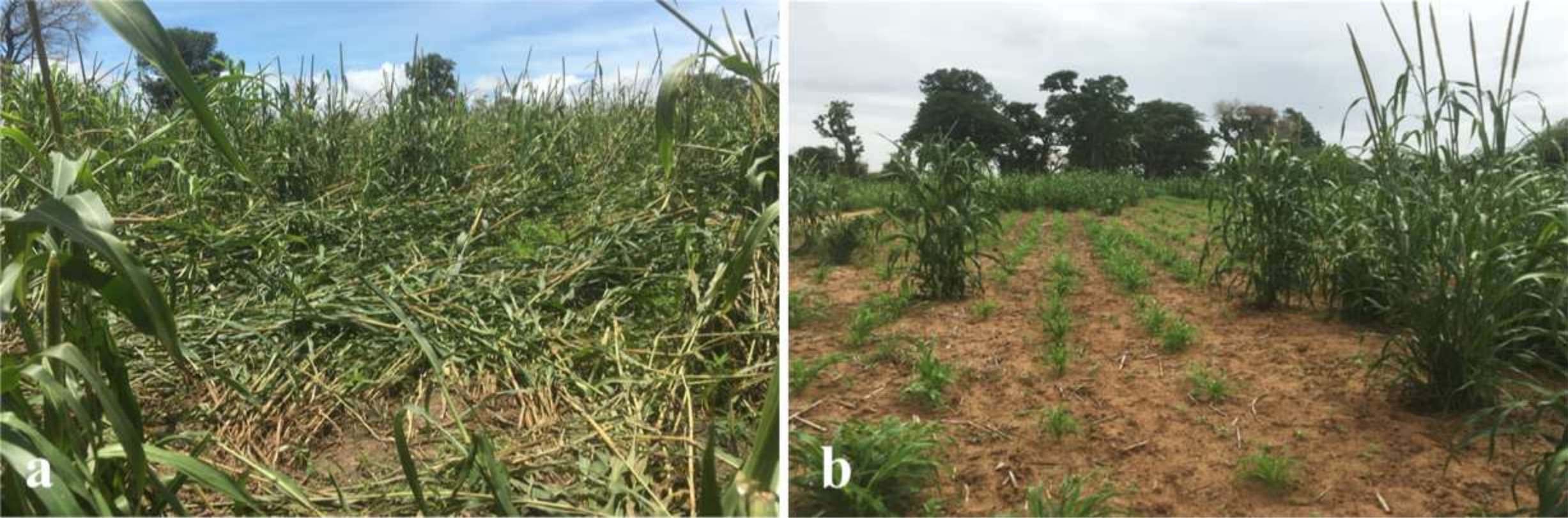

a
Slope = 0.18 ± 0.07 *
R² = 0.19
Yield stability (log)
2.0
1.5
1.0
0.5
-1
0
1
b
Slope = -0.2 ± 0.08 *
R² = 0.16
Yield standard deviation (log)
15.5
15.0
14.5
14.0
13.5
-1
0
1
c
Slope = -0.018 ± 0.07
R² = 0
Mean yield (log)
15.5
15.0
14.5
-1
0
1
Effective species diversity


a
Pearl_millet
(n = 33)
a
Roselle
(n = 26)
a
Peanut
(n = 25)
a
Watermelon
(n = 8)
ab
Sorghum
(n = 15)
ab
Cowpea
(n = 25)
b
0
2
4
6
Yield stability
b
Pearl_millet - Sanio
Pearl_millet - Souna
Pearl_millet - Guiss
Pearl_millet
Roselle - Fandan
Roselle - Vinto
Roselle
Peanut - Foure
Peanut - Essaye-moi
Peanut - Yeger
Peanut
Watermelon - Greybelle
Watermelon
Sorghum - Patch
Sorghum - Sorgho
Sorghum
Cowpea - Mbilix
Cowpea - Melex
Cowpea - Ngagne
Cowpea - Sodeva
Cowpea - Fandan
Cowpea
0
2
4
6
Yield stability


a
Pearl_millet
Sorghum
Watermelon
Peanut
Roselle
Cowpea
**
ns
ns
ns
ns
ns
0
1
Logratio
b
Pearl_millet - Souna
Pearl_millet - Guiss
Peanut - Foure
Watermelon
Sorghum - Sorgho
Sorghum - Patch
Roselle - Rouge clair
Pearl_millet - Sanio
Peanut - Yeger
Peanut - Lao
Peanut - Essaye-moi
Cowpea - Sodeva
Cowpea - Melex
Cowpea - Mbilix
Cowpea - Fandan
Roselle - Vinto
Roselle - Fandan
Cowpea - Ngagne
-1
0
1
Logratio


a
Slope = 0.11 ± 0.04 **
R² = 0.26
Yield asynchrony
0.00
0.25
0.50
0.75
-2
-1
0
1
Effective Sp diversity
b
Slope = 0.28 ± 0.09 **
R² = 0.28
0.00
0.25
0.50
0.75
0.5
1.0
1.5
2.0
Yield stability (log)


a
Seasonal rainfall (mm)
Dry spell
2020
2021
2022
2023
2024
Mean number of days for the two first dry spell
b
Total yield
Pearl Millet - Guiss
Pearl Millet - Sanio
Pearl Millet - Souna
c
Sorghum - Patch
Sorghum - Sorgho
d
Total yield
Peanut - Essaye-moi
Peanut - Lao
Peanut - Foure
Peanut - Yeger
e
Cowpea - Fandan
Cowpea - Ngagne
Cowpea - Mbilix
Cowpea - Sodeva
Cowpea - Melex
f
Roselle - Fandan
Roselle - Rouge clair
Roselle - Vinto


a
b

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