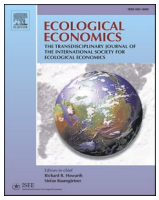
Ecological Economics 241 (2026) 108852

Contents lists available at ScienceDirect

Ecological Economics

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



ANALYSIS

Plant diversity to cope with increased drought risk in grasslands

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ARTICLE INFO

JEL:
Q150
Q510
Q570

Keywords:
Biodiversity
Risk management
Weather extremes
Nature-based solution
Insurance value

ABSTRACT

Grasslands are essential for global milk and meat production. Climate change and growing frequency of extreme weather events are expected to increase variability in production. This study explores how plant diversity can act as natural insurance against drought risks in grasslands using theoretical model and simulation. Examining sown diversity from a portfolio perspective, we identify mechanisms underlying its insurance value, including the statistical averaging effects and community asynchrony. Our findings demonstrate that, within productive grasslands, modest plant diversity can mitigate a substantial portion (37 %) of the risk, offering a sustainable climate adaptation strategy in production-oriented ecosystems.

1. Introduction

Grasslands cover more than 60 % of agricultural lands worldwide (FAO, 2021). In Europe, intensively managed grasslands are widespread and are an essential source for livestock feed[1] (Estel et al., 2018; Huyghe et al., 2014; Schwieder et al., 2022; Weber et al., 2023). Agricultural production faces significant increasing environmental risks, including extreme weather events and pest and disease pressure, which reduce crop yields and increase production risks (Arora et al., 2020; Gammans et al., 2017; Orlowsky and Seneviratne, 2012; Ray et al., 2012). Among these risks, drought is probably the most critical for temperate productive grassland systems, which are usually rainfed (Knapp et al., 2002). To increase the economic resilience of milk and meat production and to cope with extreme weather events, farmers can use various risk management strategies. A key strategy is the use of natural insurance approaches that rely on diversity, beneficial species interactions and species differences (e.g., asynchrony of growth) to stabilize yield. Such diversification strategies can be win-win measures as they provide both private benefits to farmers and public benefits due to an increase in other ecosystem services than food provision such as carbon sequestration or pollination (Isbell et al., 2011; Paul et al., 2020). Plant diversity as a natural insurance strategy is currently, however, poorly understood and underused by farmers. Therefore, understanding the role that plant diversity can play in buffering yield losses from droughts is key to creating sustainable food production systems.

In this study, we assess the economic potential of sown plant diversity as a natural insurance for grassland-based farming systems against production risk under increasing drought risk (see Table 1 for a summary of the definition of key concepts). We start with a novel theoretical analysis—serving as a conceptual foundation to the empirical section—that examines the insurance value of plant diversity (defined as the economic value linked to the reduction in yield variability resulting from increased plant diversity; see Table 1) from a portfolio perspective, i.e., considering plant diversity as a portfolio of plants. We further explore various mechanisms underlying this insurance value for the first time from an economic perspective (e.g., asynchrony as an indicator of complementarity between species). The theoretical framework lays the foundation for simulations to quantify plant diversity effects under different summer drought risk exposures, using data from grassland diversity experiments. Leveraging such experimental data allows us to avoid endogeneity issues – often linked with on-farm observations – when establishing an empirical relationship

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[1] Grasslands provide many other ecosystem services contributing to public welfare, e.g., carbon storage (Huber et al., 2022; Lopez et al., 2022). Note however, that animal-based production systems also imply various negative environmental aspects (e.g., Foley et al., 2011).

https://doi.org/10.1016/j.ecolecon.2025.108852
Received 14 April 2025; Received in revised form 21 August 2025; Accepted 4 November 2025
Available online 13 November 2025

Table 1
Summary of the definition of key concepts within this paper.

Concept	Definition and context
Insurance value of sown plant diversity	The insurance value of sown plant diversity is defined as the economic value linked to the reduction in yield variability resulting from a change in sown plant diversity.
Species interaction effect	The species interaction effect represents a part of the effect of diversity on yield variability, specifically the portion arising from ecological interactions between species that stabilize ecosystem functions (Tilman et al., 2014). This effect is attributed to interspecific complementary in the use of resources (e.g., soil nutrients) resulting from differences in plant species characteristics. These ecological effects can occur only when different plant species are sown in the same field.
Statistical averaging effect	The statistical averaging effect represents a part of the effect of diversity on yield variability, namely the portion arising from averaging individual species' biomass yield. This effect is purely statistical and stems from imperfect correlations between the biomass production of different species, similar to the case of financial assets (Doak et al., 1998; Koellner and Schmitz, 2006; Tilman et al., 1998). This statistical effect can occur even when different species are sown in separate fields, i.e., when only one species is sown in a field and the overall performance is evaluated across many fields.
Asynchrony	Community asynchrony quantifies the extent to which the temporal growth patterns of different species complement each other (Loreau and de Mazancourt, 2008). We consider asynchrony as a property of diversity that estimates dissimilarities in the response of species' growth within a year (allowing us to take into account the complementarity of species and not only their number or proportions).
Drought risk	Drought risk is defined here as the probability of a summer drought.
Production risk	Production risk is defined as the variability in agricultural yield due to uncertainty in the growth dynamics of crops or grass (e.g., influenced by weather conditions or management practices) (Komarek et al., 2020). To describe production risk, we use the variance and skewness of profit because they allow to analyze the variability of farmers' profit with an emphasis on downside risk, including some tail behavior.

between plant diversity and yield risk.

In previous literature, especially ecological studies have addressed the effect of plant diversity on grassland production and stability[2] (e.g., Finn et al., 2013; Loreau et al., 2021; Tilman et al., 1996). The diversity effect consists of two main components. First, the mean production often increases with a higher diversity of plants due to, for example, increased resource use in space and time or beneficial nutrient-cycling feedbacks (Finn et al., 2013; Marquard et al., 2009; Nyfeler et al., 2009, 2011; Tilman et al., 1996, 2014). Second, higher plant diversity has been shown to decrease the overall variation of biomass production (Hector et al., 2010; Isbell et al., 2009; Loreau et al., 2021; Suter et al., 2021). When considering the effect of diversity under varying drought risk, the ecological literature provides mixed results. Studies find a positive effect of diversity on drought resistance (Isbell et al., 2015). Moreover, studies find that the positive effect of diversity on yield persists under drought conditions but find no significant differences between the drought losses for different levels of diversity (Grange et al., 2021; Haughey et al., 2018; Hofer et al., 2016). Finally, some studies find that diversity can actually decrease the resistance against drought such that drought losses would increase in the case of higher diversity, the effect arising through greater losses of (diversity-induced) higher pre-drought biomass (Pfisterer and Schmid, 2002; Van Ruijven and Berendse, 2010).

When it comes to the effects of diversity on yield variability, two elements can be distinguished (Table 1). First, ecological interactions between species stabilize ecosystem functions due to complementarity between species (Tilman et al., 2014). This is explained by a more optimal use of resources (e.g., soil nutrients) due to differences in plant species characteristics. Such complementary effects can only occur if the different plant species are established in the same field. Second, overall biomass production can also be stabilized from a statistical ground[3] through averaging individual species biomass, the effect arising due to imperfect correlations between the biomass production of the different species (Doak et al., 1998; Koellner and Schmitz, 2006; Tilman et al., 1998). In other words, farmers can grow different plant species (even in different fields), thereby reducing yield variability, just as would be the case with different financial assets. Hereafter, we refer to those effects as 'species interaction effect', and 'statistical averaging effect', respectively.

Economic studies have investigated the economic value of biodiversity in natural or production-oriented ecosystems theoretically (e.g., Augeraud-Véron et al., 2019; Baumgärtner, 2007; Baumgärtner and Quaas, 2010; Baumgärtner and Strunz, 2014; Quaas and Baumgärtner, 2008) and empirically (e.g., Chavas et al., 2022; Di Falco and Chavas, 2006, 2009; Finger and Buchmann, 2015; Schaub et al., 2020a, 2020b). Biodiversity has been shown to increase the economic value of ecosystems through a higher mean production and, for risk averse decision makers, also through reduced variability, while 'downside risk' (e.g., represented by the skewness) has rarely been addressed in this literature (Di Falco and Chavas, 2006, 2009). However, increased diversity is often more costly to achieve (Schaub et al., 2021; Török et al., 2011).

Furthermore, only few studies investigated diversity through a portfolio perspective to infer profitability from species richness (Binder et al., 2018; Koellner and Schmitz, 2006), with species considered as assets making up the farmer's portfolio. In this literature, the community asynchrony variable (Loreau and de Mazancourt, 2008), which is based on the differences between individual species' growth, could serve to explore the synergies among species. Community asynchrony quantifies the extent to which the temporal growth patterns of different species complement each other. In the agricultural context, asynchrony may serve as a fundamental property to explain the effect of diversity on yield (Husse et al., 2016, 2017) and yield stability (Egli et al., 2020). However, despite the importance of this property it has not been considered in the economic assessment of plant diversity.

We contribute to the literature in three ways. First, as a conceptual foundation to the empirical section, we explore a novel theoretical approach to deriving natural insurance properties (insurance value) from diversification strategies in production-oriented ecosystems. More specifically, we conduct an economic analysis of sown plant diversity from a portfolio perspective, with a focus on its risk-reducing properties. Second, we contribute to the debated literature by exploring sown plant diversity as a risk management instrument against drought risk. To this end, we empirically quantify the effect of diversity on yield variance and skewness and we derive the insurance value from diversity under different summer drought risk exposures. This method allows us to account for the effect of plant diversity especially on downside risks. Third, we address theoretically and empirically the mechanisms underlying the risk-reducing effect of sown plant diversity, lacking in previous economic assessments. Specifically, we i) separate the effect derived from ecological interactions between individual species (i.e., species interaction effect) from the statistical effect through averaging, caused by imperfect correlations of the species' biomass production (i.e., statistical

[2] Stability as used here refers to both the mean and variation of yield. It is calculated as: stability = mean yield / standard deviation of yield.

[3] Here, the statistical effect through averaging can include both, inherent differences in growth performance of the species and random fluctuations of species performance over time, therefore part of the statistical effect can also be on ecological grounds.

averaging effect) (Koellner and Schmitz, 2006; Tilman et al., 1996, 1998) and ii) consider asynchrony as a property of diversity that estimates dissimilarities in the response of species' growth within a year, allowing us to take into account the complementarity of species and not only their number or proportions (see Table 1). These contributions are of policy relevance, as they help to understand to what extent and how plant diversity can function as an economic natural insurance in the face of increasing drought risk.

Our main results suggest that plant diversity reduces the risk for farmers by decreasing yield variance. However, we find that plant diversity at the same time increases the downside risk by contributing to more negative yield skewness. The net effect on farmers' risk premium is negative, demonstrating that plant diversity offers a positive insurance value. Moreover, the findings remain constant even under higher levels of drought risk exposure, thus showing the potential of sown plant diversity as risk management instrument under more risky conditions. Finally, the statistical averaging effect is determined to be the primary contributor to the insurance value, rather than the species interaction effect.

The remainder of the paper is organized as follows. First, we develop a theoretical framework to model farmers' choice of diversity and natural insurance mechanisms. Second, we quantify the impact of diversity on production under different risk exposures based on grassland yield data from drought stress experiments.

2. Theoretical framework

In this section, we develop a theoretical economic model—serving as a conceptual foundation to the empirical section—to study the insurance value of sown plant diversity in sown productive grasslands, focusing on risk reduction. To this aim, we build on the model by Baumgärtner (2007) and use a novel portfolio approach to describe sown plant diversity as drought insurance. In our model, farmers choose the level of sown plant diversity n (later referred as 'plant diversity' only) and generate profit through grassland yields from intensively managed grasslands. Additionally, we consider that farmers sow the different plant species in equal proportions[4] to keep the analytical steps tractable and because species interactions are higher under uniformity of species abundance (Kirwan et al., 2007). We examine the uncertain profit of farmers in a given year, defined as:

$$\pi = P \times \sum_{i=1}^{n} l_i \widehat{Y}_i(n, d, x) - c(n) - C(x) \tag{1}$$

where π represents the profit of farmers per hectare. P is the price of hay per kg. l_i is the share of species i in the fields. $Y_i(n, d, x)$ is the yield (per hectare) of species i expressed in dry matter biomass[5] in kg ha^{-1}. $\sum_{i=1}^{n} l_i Y_i(n, d, x)$ is the portfolio of the different sown plant species—i.e., the total yield sold at the hay price—assuming only agronomically relevant species are used (Schaub et al., 2020a; Schaub et al., 2021). Drought risk is modelled via variable d describing the frequency of summer droughts, unknown to farmers. A drought is considered to have occurred in a summer when the precipitation level falls below a certain threshold (Bucheli et al., 2021). Therefore, we consider drought occurrences as random binary events that follow a Bernoulli distribution. For simplicity, we assume that yearly drought events are independently distributed (Mishra and Singh, 2011; Wu et al., 2020). Both sown plant diversity n and drought risk d affect the yield distribution of the different species. Plant diversity affects the species' mean yield through mechanisms such as beneficial nutrient-cycling feedback (Nyfeler et al., 2009, 2011; Tilman et al., 1996, 2014) and drought risk generally decreases the yield (Hofer et al., 2016; Grange et al., 2021). Variable x represents all the other weather and management variables. We assume that these variables are either random variables unknown to the farmers (e.g., temperature) or deterministic and fixed (e.g., fertilizer). Therefore, in our model the variables represented by x affect the yield distribution, but this effect is fixed. $c(n)$ is the part of the farmer's cost of production per hectare related to species diversity. This cost is increasing in n, meaning that a higher diversity is more costly for farmers due to the higher cost of more diverse seed mixtures (Schaub et al., 2021). We assume that farmers maximize their expected utility, $E(U)$, by choosing the number of species, n, sown in their fields. For this section, variable n can also represents a diversity index that also consider evenness (e.g., Shannon index). $C(x)$ is the cost of production per hectare unrelated to species diversity. As we focus on yields and how plant diversity affects yields, P, $c(n)$ and $C(x)$ are assumed to be deterministic and not affected by droughts. We assume that i) grassland management costs depend mostly on management decisions (e.g., fertilizer input, number of cuts, sown mixtures) and ii) that farmers use other feed sources than grass such that shortage in grassland yields due to drought may not affect the hay prices.

We described above that we consider farmers that maximize their expected utility. Specifically, to describe the expected utility of farmers we consider a power utility function: $E(U) = \pi^{1-\tau}/1-\tau$ (Di Falco and Chavas, 2006). Where τ represents the coefficient of relative risk aversion. Furthermore, we assume that farmers are risk averse (Iyer et al., 2020), thus the absolute Arrow Pratt coefficient of risk aversion is defined as $r_2 = -U''/U' = \tau/E(\pi) > 0$ (Arrow, 1964; Pratt, 1964). Moreover, we consider downside risk averse farmers, thus the coefficient of absolute downside risk aversion is defined as $r_3 = -U'''/U' = -\left(\tau^2+\tau\right)/(E(\pi))^2 < 0$ (Di Falco and Chavas, 2006).

Maximizing the expected utility is equivalent to maximizing the certainty equivalent: $CE = E(\pi) - RP$. The risk incurred by farmers is captured by the risk premium (Chavas, 2004). The risk premium per hectare can be approximated by (Di Falco and Chavas, 2006)[6]:

$$RP = \frac{1}{2} r_2 var(\pi) + \frac{1}{6} r_3 ske(\pi) \tag{2}$$

2.1. Insurance value

We derive insights about the value of diversity as natural insurance using the effects of diversity on the risk premium. Specifically, we derive the insurance value per hectare, IV, (negative of the first derivative of the risk premium with respect to plant diversity) and the total insurance value per hectare, $totIV$ [7](integral of the insurance value for a certain diversity level) (Baumgärtner, 2007):

[4] Other types of management may include self-seeded permanent grasslands (Reheul et al., 2007). Here diversity controlled by seeding is key for farmers to significantly influence the diversity level of grasslands.

[5] Previous studies found modest to negligible effects of plant diversity on yield quality in sown grasslands with productive species (Schaub et al., 2020a; Suter et al., 2021). Thus, considering dry yield biomass (and neglecting the differences in nutritional value of plant species) is adequate to assess effects of plant diversity on farmers' income.

[6] This approximation provides a local representation of the risk premium, which could be extended to incorporate higher moments of the distribution (e.g., Wang et al., 2021). Kurtosis was also considered, both theoretically and empirically (see supplementary material 8). Empirically, the added value of considering kurtosis —both in economic terms and for the mechanisms we aim to disentangle—is small (see supplementary material 8). For the main analysis, we therefore focus on variance and skewness, ensuring consistency between the theoretical framework and the empirical implementation (e.g., Di Falco and Chavas, 2006; Groom et al., 2008). While the presented approximation of the risk premium represents a local approximation (i.e., under small changes), we believe it is still insightful to learn for non-local scenarios. However, this limitation should be considered (see Pratt, 1964).

[7] Note that n_o is the minimum diversity level. If n represents plant richness, then $n_o = 1$. If n represents the Shannon index $n_o = 0$.

$$IV(n) = -\frac{\partial RP}{\partial n} = -\frac{1}{2}r_2\frac{\partial var(\pi)}{\partial n} - \frac{1}{6}r_3\frac{\partial ske(\pi)}{\partial n} \quad (3)$$

$$totIV(n) = \int_{n_0}^{n}\left(-\frac{\partial RP}{\partial n}\right)dn = \int_{n_0}^{n}\left(-\frac{1}{2}r_2\frac{\partial var(\pi)}{\partial n} - \frac{1}{6}r_3\frac{\partial ske(\pi)}{\partial n}\right)dn \quad (4)$$

The insurance value (eq. (3)) shows the effect of sown plant diversity on the profit distribution, and we describe it here as a composite of the effect of plant diversity on skewness and variance of yield as both risk and downside risk are considered. On the one hand, according to previous literature, we expect the effect of diversity on total yield variance to be negative and therefore positively affect the insurance value (e.g., Loreau et al., 2021). On the other hand, the effect of diversity on yield skewness is generally unknown and remains to be determined empirically. The total insurance value (eq. (4)) describes the total monetary benefit for the farmers from using a specific level of diversity (n) instead of a monoculture[8].

The optimal plant diversity choice is found when the marginal benefit of increased diversity (increased mean revenues and decreased risk) equal the marginal cost of increased diversity (e.g., increased cost of mixtures), i.e., when the derivative of the certainty equivalent with respect to plant diversity equals zero: $\partial CE/\partial n = \partial E(\pi(n,d,x))/\partial n + IV = 0$. Considering our empirical analysis (with a maximum plant species richness of four), it is noteworthy that yield increases on average with higher diversity; yet, the costs for such levels of diversity change only slightly (Schaub et al., 2021). As a result, the optimal diversity level would be the maximum diversity in our sample. This is because we focus on highly productive, intensively managed grasslands with high cutting frequencies of up to six times per year and nitrogen input, where a small number of plant species especially adapted to this management will quickly outcompete all the other less adapted species. Maintaining higher levels of diversity would require unrealistically high re-sowing frequencies to replace the simplified plant community by a new, diverse one (Gossner et al., 2016; Van Den Pol-van Dasselaar et al., 2020).

Furthermore, we investigate the insurance value of plant diversity under increasing drought risk. As noted above, according to findings from ecological studies (Grange et al., 2021; Haughey et al., 2018; Hofer et al., 2016) the effect of diversity on the risk premium under varying drought risks may lead to three potential outcomes described in Fig. 1 and eq. (5):

$$\frac{\partial IV(n)}{\partial d} = -\frac{\partial^2 RP}{\partial n \partial d} = -\frac{1}{2}r_2\frac{\partial^2 var(\pi)}{\partial n \partial d} - \frac{1}{6}r_3\frac{\partial^2 ske(\pi)}{\partial n \partial d} \quad (5)$$

The key elements to understand how the insurance value of diversity changes when drought risk increases are the second derivative of biomass yield variance and skewness with respect to diversity and drought risk exposure $\frac{\partial^2 var(\pi)}{\partial n \partial d}$ and $\frac{\partial^2 ske(\pi)}{\partial n \partial d}$. From the ecological literature, we cannot conclude on their sign (see Section 1 and Fig. 1), and the magnitude and sign of the changes in insurance value due to diversity needs to be assessed empirically. For instance, a positive value from eq. (5) would signify that the monetary benefit of farmers from diversity increases under higher drought risk (shown in fig. 1a).

2.2. Mechanisms

In the following two subsections, we investigate various mechanisms underlying the insurance value of diversity in grasslands.

2.2.1. Species interaction effect vs. statistical averaging effect

For studying theoretically the species interaction and statistical averaging effects, we introduce simplifying assumptions. Specifically, we assume that the yields of each individual plant species follow the same distribution, implying identical mean, variance and skewness. We further consider that the variance and skewness of individual plant species are affected identically by each of drought risk and plant diversity[9]. These assumptions are necessary for a stylized simplification that allows us to theoretically disentangle the species interaction effect from the statistical averaging effect, a distinction also examined in previous literature (Koellner and Schmitz, 2006; Tilman et al., 1996, 1998). These assumptions affect how the statistical averaging effect is represented, as there are no differences in mean, variance, or skewness between species. As a result, the correlation between yields of different species is treated as the sole driver of the statistical averaging effect. This may lead to an underestimation of the statistical averaging effect, but it will not alter the overall outcome, which is that plant diversity reduces income risk through statistical averaging (see supplementary material 6 for additional details). In the empirical analysis, we do not make these assumptions and consider plant species with different distribution and different reaction to drought.

The variance and skewness of profit per hectare, focusing on plant diversity and droughts, can be described as (Robison and Barry, 1987):

$$var(\pi) = P^2\frac{1}{n}(1+(n-1)\rho)\sigma^2(n,d) \quad (6)$$

$$ske(\pi) = P^3\frac{1}{n^2}(1+(n^2-1)s)\sigma^3(n,d) \quad (7)$$

where ρ represent the average correlation between species such that: $\rho = \frac{1}{n(n-1)}\sum_{i=1}^{n}\sum_{j\neq i}^{n}\rho_{ij}$. s is defined as the average co-skewness coefficient between the different species such that: $s = \frac{1}{n(n^2-1)}\sum_{i=1}^{n}\sum_{j=1}^{n}\sum_{i=j\to k\neq i=j}^{n}s_{ijk}$ (Friend and Westerfield, 1980).

Drought risk affects the variance and skewness of profit through its impact on the variance and skewness of individual species yields. For keeping the model tractable, and without impacting the direction of the effects, we assume that drought risk does not impact the correlation between species (Muraina et al., 2021). We consider that plant diversity affects the profit distribution in two ways. First, it impacts the variance and skewness of profit by affecting individual species yield due to their interactions. Second, it impacts the variance and skewness of profit statistically depending on the average correlation within the portfolio framework.

We use eqs. (6) and (7) to develop the variance and skewness terms from our insurance value analysis. This allows us to decompose the effect of plant diversity on the variance and skewness of yield in two distinct components: the species interaction effect and the statistical averaging effect (see Section 1 for description).

From eq. (3), (6) and (7) the insurance value is described as:

$$\begin{aligned} IV(n) &= -\frac{\partial RP}{\partial n} \\ &= \left\{\frac{1}{2}r_2P^2\frac{1}{n^2}(1-\rho)\sigma^2(nd) + \frac{1}{3}r_3P^3\frac{1}{n^3}(1-s)\,\sigma^3(nd)\right\} + \left\{\right. \\ &\quad -\frac{1}{2}r_2P^2\frac{1}{n}(1+(n-1)\rho)\frac{\partial\sigma^2(nd)}{\partial n} - \frac{1}{6}r_3P^3\frac{1}{n^2}(1+(n^2 \\ &\quad \left.-1)s)\frac{\partial\sigma^3(nd)}{\partial n}\right\} \end{aligned} \quad (8)$$

The insurance value of plant diversity is composed of two distinct components, indicated by the (curly) braces in eq. (8). Moreover, each component can be separated in two parts: i) relating to variance (risk) and ii) relating to skewness (downside risk). Regarding the first component, an increase in diversity changes the variance and skewness

[8] To compare with the empirical part, where plant diversity is represented by the Shannon index, we use an integral to describe the total insurance value. Thus, we treat richness as a continuous variable.

[9] However, this assumption is not required for the empirical analysis below, so we relax it there.

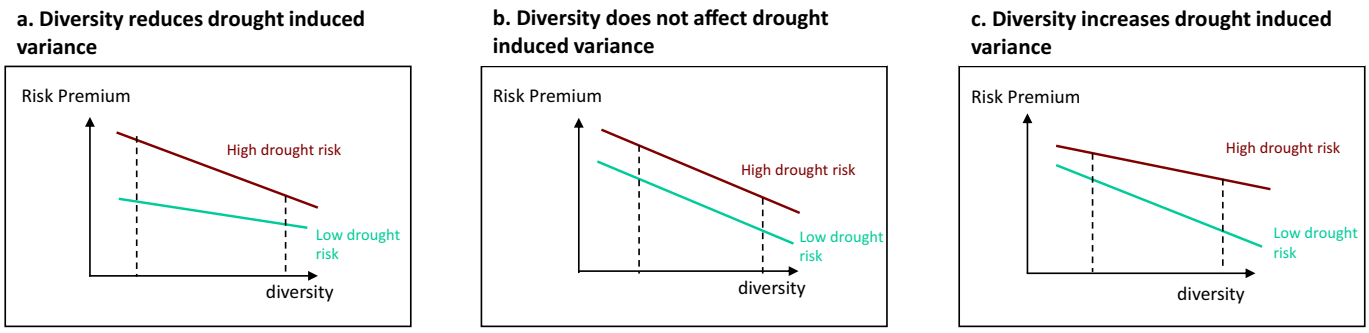

Fig. 1. Potential outcome for natural insurance under varying drought risk.
Note: Panel a) represents the potential outcome, where the insurance value of diversity is stronger under high than under low drought risk. Panel b) represents the potential outcome, where the insurance value of diversity does not differ between high and low drought risk. Panel c) represents the potential outcome, where the insurance value is lower under high than under low drought risk.

of profit depending the average correlation and average co-skewness of individual species yield. This represents the statistical averaging effect derived from imperfect correlations and imperfect co-skewness between species. Regarding the variance part, as long as the average correlation between species is below the maximum value of +1, the following is implied from eq. (8):

$$\frac{1}{2}r_2P^2\frac{1}{n^2}(1-\rho)\sigma^2(n,d) > 0 \tag{9}$$

This means that an increase in diversity would decrease the risk premium through the statistical effect leading to some potential gains of diversification.

Regarding the second component, an increase in diversity changes the variance and skewness of profit depending the effect of diversity on individual species variance $\frac{\partial\sigma^2(n,d)}{\partial n}$ and the effect of diversity on individual species skewness $\frac{\partial\sigma^3(n,d)}{\partial n}$. This represents the effect derived from species interactions. Regarding the variance part, generally previous ecological literature finds that individual species variance increases with diversity such that: $\frac{\partial\sigma^2(n,d)}{\partial n} > 0$ (Hector et al., 2010; Tilman et al., 1996), thus implying from eq. (8):

$$-\frac{1}{2}r_2P^2\frac{1}{n}(1+(n-1)\rho)\frac{\partial\sigma^2(n,d)}{\partial n} < 0 \tag{10}$$

This means that an increase in diversity would increase the risk premium through the species interaction effect.

The separation in two distinct components (i.e., the species interaction effect and the statistical averaging effect) remains the same when examining the insurance value, as well as when examining changes in insurance value under increasing drought risk (see supplementary material 1 for details). Thus, while some relationships need to be assessed empirically, our theoretical analysis highlights that the insurance value of plant diversity may increase or decrease under higher drought risk exposure through two different effects (i.e., species interaction effect and statistical averaging effect). Moreover, even when the species interaction effects of insurance value (if $\frac{\partial\sigma^2(n,d)}{\partial n\partial d} \geq 0$) are neutral or negative, greater plant diversity may still be a viable risk management strategy due to the statistical averaging effect. Additionally, this decomposition into two components also holds when considering higher moments of the distribution, such as kurtosis (see supplementary material 8).

The correlation between individual species' yields is one of the keys to the effect of statistical averaging of insurance value. Lower average correlation, which signals low plant community synchrony (Bjørnstad et al., 1999; Loreau and de Mazancourt, 2008), leads to higher insurance value for farmers. Generally, we can expect that plant species within the same functional group exhibit stronger correlations in growth patterns compared to those across different functional groups (Roscher et al., 2011); thus, we anticipate the statistical averaging effect of insurance value to be higher for mixtures with species coming from different functional groups. Specifically, in sown productive grasslands, farmers can strategically select species to maximize complementarity in temporal growth and can do so at low levels of richness. Consequently, we expect the effect of diversity on total yield variance to saturate quickly at higher richness levels (Lüscher et al., 2022).

2.3. Asynchrony variable

In this subsection, we investigate plant community asynchrony (1 - φ) as a property of diversity to account for the complementarity between species (Loreau and de Mazancourt, 2008).

When deciding about plant diversity to reduce adverse effects of drought risk, farmers might not only consider the number of plant species and their share in a community but also the differences between these species. In the ecological literature, community asynchrony is used to describe the dissimilarities in the response of species' growth (Hautier et al., 2014; Loreau and de Mazancourt, 2008; Zhao et al., 2022). Following ecological literature, community-wide species asynchrony is defined as (Loreau and de Mazancourt, 2008):

$$1-\varphi = 1-\frac{{\sigma_T}^2}{\left(\sum_{i=1}^{n}\sigma_i\right)^2} \tag{11}$$

where φ represent the community yield synchrony. ${\sigma_T}^2$ is the total yield temporal variance and σ_i the yield temporal standard deviation of species i. This temporal variance and temporal standard deviations are calculated based on the yield variation across harvests within a year, following Haughey et al. (2018). Therefore, the asynchrony variable we are considering can be integrated into our model, which accounts for a single year with uncertain outcome, as it only reflects changes in yield between cuts within that year. Ecological literature finds that asynchrony is an important factor of yield stability with and without drought consideration (Egli et al., 2020; Haughey et al., 2018; Muraina et al., 2021).

The variance of profit is now described by the following equation:

$$var(\pi) = P^2{\sigma_c}^2(n,d,1-\varphi) \tag{12}$$

$$ske(\pi) = P^3{\sigma_c}^3(n,d,1-\varphi) \tag{13}$$

where ${\sigma_c}^2(n,d,1-\varphi)$ is the community variance per hectare and represents the total yield variance from all species in the field. ${\sigma_c}^3(n,d,1-\varphi)$ is the community skewness per hectare and represents the total yield skewness from all species. The community variance and community skewness vary with plant diversity, drought risk and asynchrony. We define the effect of community asynchrony on variance as:

$\partial {\sigma_c}^2/\partial 1-\varphi<0$, meaning that community variance decreases when asynchrony increases. In other words, the higher asynchronous the temporal development of species in a community, the lower community variance and therefore the lower profit variance. The effect of asynchrony on community skewness remains an open question.

The economic implications of considering asynchrony as property of diversity are described through the insurance value, *IV*, of plant diversity and the change in insurance value with respect to drought risk:

$$IV(n) = -\frac{\partial RP}{\partial n} = -\frac{1}{2}r_2P^2\frac{\partial {\sigma_c}^2(n,d,1-\varphi)}{\partial n} - \frac{1}{6}r_3P^3\frac{\partial {\sigma_c}^3(n,d,1-\varphi)}{\partial n} \quad (14)$$

$$\frac{\partial IV(n)}{\partial d} = -\frac{\partial^2 RP}{\partial n \partial d} = -\frac{1}{2}r_2P^2\frac{\partial^2 {\sigma_c}^2(n,d,1-\varphi)}{\partial n \partial d} - \frac{1}{6}r_3P^3\frac{\partial^2 {\sigma_c}^3(n,d,1-\varphi)}{\partial n \partial d} \quad (15)$$

The insurance value per hectare of plant diversity, $IV(n)$, is assumed positive and the change in insurance value with respect to drought risk $\frac{\partial IV(n)}{\partial d}$ is undefined (see Section 2.1). The community asynchrony variable is relevant for decision makers as it may affect the relation between plant diversity and community variance and skewness, therefore also affecting the insurance value of diversity. From previous literature (Haughey et al., 2018; Hector et al., 2010; Suter et al., 2021; Tilman et al., 2014) we expect a stabilizing effect on community yield as plant diversity increases (i.e. lower variance), the stabilizing effect being partly mediated through higher species asynchrony, leading to higher insurance value for more asynchronous plant communities. The effect of asynchrony on the change in insurance value with respect to drought remains, however, unexplored.

2.4. Summary of the theoretical insights

In this theoretical framework, the main insights can be summarized regarding three aspects. First, the insurance value of plant diversity is a composite of the effects on variance and skewness of yield if both risk and downside risk are considered. As a result, the economic insurance value varies with the degree of risk and downside risk aversion of farmers. Second, the effect of diversity on yield consists of two sub-effects: i) the effect derived from species interactions and ii) the statistical averaging effect derived from imperfect correlation and imperfect co-skewness between species. Third, we find that increasing community asynchrony could be a mechanism by which farmers can benefit from the insurance effects of diversity.

3. Data

To conduct the analysis, we use yield data of two coordinated grassland field experiments in Switzerland, representing intensively managed sown grasslands. One experiment ran for two years (Finn et al., 2018, site Switzerland 1), the other for one year (Hofer et al., 2016, site Switzerland 2), resulting in data from three site-years (see Fig. 9 in supplementary material 7 for the location of the experiments). Although the data covers a relatively short period (three years in total), our analysis remains highly relevant thanks to a resampling strategy that effectively simulates a longer timeframe (Section 4). The experiment included various levels of diversity. The plots were sown in four different monocultures (plant species = 1) and eleven different mixtures (plant species >1) using four different high yielding species: one grass and one herb and two legumes that are commonly used in high performing grassland systems in Europe. The four species are: *Lolium perenne, Cichorium intybus, Trifolium repens and Trifolium pratense.* The mixtures were sown with either two or four species and different shares of the species, specifically: mixture type 1: 50 % of each of two species; mixture type 2: 79 % of one species, 7 % of each of the other three species; mixture type 3: 25 % of each of the four species. Considering that four species were used for mixtures, the experiment included six different compositions of mixture type 1, four different compositions of mixture type 2, and one composition of mixture type 3 (see Hofer et al., 2016 for more details on the design). Overall, our dataset consists of 206 plot observations across three site-years, 15 diversity treatments, and two drought conditions, with three replicates each (note that not all diversity treatments were implemented at every site or replicate). A main advantage of using experimental data is that the level of sown plant diversity is exogenous to weather and soil conditions, allowing us to identify its causal effect on productivity and its variability.

We use the Shannon index to describe the plant diversity of those plots (Shannon, 1948):

$$Shannon\ Index = -\sum_{i=1}^{n} p_i \ln(p_i) \quad (16)$$

Thus, for the monocultures and the different mixture types 1 to 3, we obtain the following values for this index: 0, 0.69, 0.74, 1.39, respectively.

The experiment was strictly following guidelines for real life farming practices in the lowlands of Switzerland. The species that were selected are high-yielding and widely used by farmers in temperate regions worldwide. Fields were cut 5 (Switzerland 2) or 6 times (Switzerland 1) and each plot of the same site received the same amount of mineral N fertilizer: 200 kg N ha^{-1} $year^{-1}$ for Switzerland 1 and 145 kg N ha^{-1} $year^{-1}$ for Switzerland 2. These values of N fertilizer and cutting frequency follow the recommendations for intensively managed grasslands in Switzerland (Huguenin-Elie et al., 2017). For more details to sward establishment and management see Hofer et al. (2016).

Across the grassland plots at each site, a summer drought was imposed in that a randomly selected half of the plots was covered with rainout shelters for nine to ten weeks in the summer to simulate an extreme drought. The rainout shelters excluded all precipitation and caused soil moisture to drop persistently below the critical level of plant accessible soil water (Hofer et al., 2016). Thus, each annual yield data observation has a variable indicating whether a drought was simulated (drought = 1) or not (drought = 0)[10]. In our analysis, drought risk exposure was defined by the shares of observations with a drought treatment in sub-samples. We simulate three drought frequency scenarios: 0 % (without), 20 % (low) and 40 % (high) (Schaub and Finger, 2020).

4. Empirical methods

Here we aim to quantify the main effects identified in the theoretical framework. Specifically, we undertake an ex-ante analysis to understand changes of the insurance value of sown diversity when summer drought risk increases. Our empirical work is organized in two parts reflecting our theoretical insights (see Fig. 2). First, we assess the effect of diversity on the variance and skewness of yield to determine the insurance value for two different levels of summer drought risk exposure (*Section 4.1*). Second, we empirically investigate the mechanisms underlying the effect of diversity on the variance and skewness of yield (*Section 4.2*). To this end, we i) use two distinct diversity gradients (i.e., diversity within fields and diversity across fields within a system) to empirically disentangle the species interaction and the statistical averaging effect outlined in the theoretical analysis and ii) perform a controlled direct effect analysis to differentiate between merely increasing diversity and considering community asynchrony involved when increasing diversity.

[10] No natural drought occurred during the years of the experiment. This ensures that the drought treatments were distinctly set up and that the counterfactual conditions received normal precipitation (Hofer et al., 2016).

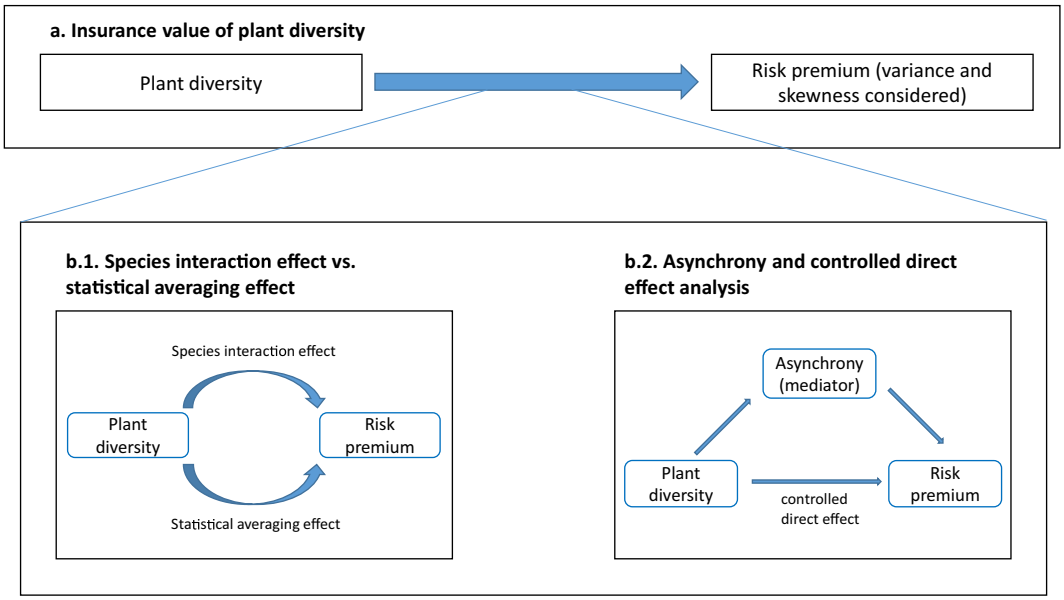

Fig. 2. Overview of the tested mechanisms underlying the effect of plant diversity.
Note: Panel a) describes the effect of plant diversity on the risk premium, i.e., the insurance value of plant diversity *(Section 2.1 and 4.1)*. Panel b.1) and panel b.2) describe the underlying mechanisms shown in our theoretical framework *(Section 2.2)* and tested in our empirical analysis *(Section 4.2)*. More specifically, panel b.1) describes the separation of the insurance value of diversity in two distinct components: the species interaction effect and the statistical averaging effect. Panel b.2) describes the controlled direct effect analysis used to differentiate between the effect mediated by asynchrony and the direct effect of diversity.

4.1. Estimation of insurance value

Here we test whether the insurance value of diversity is higher, similar or lower when drought frequency increases. It is decomposed in two steps: i) we conduct an econometrical assessment to evaluate the effect of plant diversity on the variance and the skewness of yield and ii) we assess the economic importance of those effects on the insurance value.

4.1.1. Diversity effect on variance and skewness

First, we estimate the variance and skewness of yield from eq. (2) and the effect of plant diversity on yield variance and skewness (as specified in eq. (3)) by using a stochastic production function[11] (based on the moment-based approach) (Antle, 1983):

$$y_{i,d} = \alpha_{1,d} + \beta_{1,d} n_i^{0.5} + \beta_{4,d} Site_i \times Year_i + e_{1,i,d} \quad (17)$$

$$Var\left(y_{i,d}\right) = e_{1,i,d}^2 \rightarrow Var\left(y_{i,d}\right) = \alpha_{2,d} + \beta_{2,d} n_i^{0.5} + \beta_{5,d} Site_i \times Year_i + e_{2,i,d} \quad (18)$$

$$Ske\left(y_{i,d}\right) = e_{1,i,d}^3 \rightarrow Ske\left(y_{i,d}\right) = \alpha_{3,d} + \beta_{3,d} n_i^{0.5} + \beta_{6,d} Site_i \times Year_i + e_{3,i,d} \quad (19)$$

where $y_{i,d}$ represents annual dry matter biomass yield (in ton per hectare) of observation i depending on the drought risk exposure d. n_i represents the plant diversity level modelled through the Shannon index (see supplementary material 4 for different diversity indicators). This estimate of diversity considers that all mixtures with identical shares have the same Shannon index. As we do not compare the best performing species at each diversity level, this challenges the representation of opportunity cost. This is accounted for in our analysis for two reasons: i) the experimental grassland dataset used includes only high performing species (four) that are standard choices of farmers (Hofer et al., 2016), and ii) farmers can select high performing species, yet they may not consistently pinpoint the best performing ones since these can vary from year to year (Finn et al., 2013). The diversity effect n_i is modelled by a square root term because it enables us to describe a saturation of the diversity effect with increasing species diversity (Hooper et al., 2005; Lüscher et al., 2022; Schaub et al., 2020a). $Site_i \times Year_i$ are control dummies to account for differences between sites and year. $Var\left(y_{i,d}\right)$ and $Ske\left(y_{i,d}\right)$ are the variance and skewness of yield for observation i, depending on the drought risk exposure d, estimated from the first stage regression.

We use the cross-plot variance based on annual yield observations in order to approximate the annual yield uncertainty for a single plot. We use this method due to the lack of long-time series data in such intensively managed grassland experiments. A drawback of this approximation is that we cannot identify all potential effects on the variance across years. However, we expect the cross-plot variance to capture most of the variance derived from plant growth and their interactions, while underestimating the effect derived from environmental disturbance other than extreme summer droughts, since the latter are accounted for in our analysis.

To account for varying drought risk exposures, we conduct stratified random sampling (with replacement). In this empirical method, we consider that the probability of a summer drought represents drought risk exposure. Annual yield observations are selected unequally from two sub-datasets representing drought conditions (in which drought was simulated for all observations) and ambient, normal conditions (in which no drought was simulated for all observations) (see Fig. 3). Using this sampling method, three scenarios are evaluated: without drought (in which we select 100 % of observations without a drought treatment), low drought risk exposure (in which we select 20 % of observations with, and 80 % of observations without a drought treatment) and high drought risk exposure (in which we select 40 % of observations with, and 60 % of observations without a drought treatment). This sampling strategies is implemented 10,000 times for each drought risk exposure scenario. Then, the econometric analysis is conducted on each subsample, thus following a bootstrap regression strategy of 10,000 iterations for each drought risk exposure scenario.

[11] We focus on a yearly perspective and analyze resistance (defined as the ability to maintain stable production in the face of climatic variations), and neglect dependencies across years.

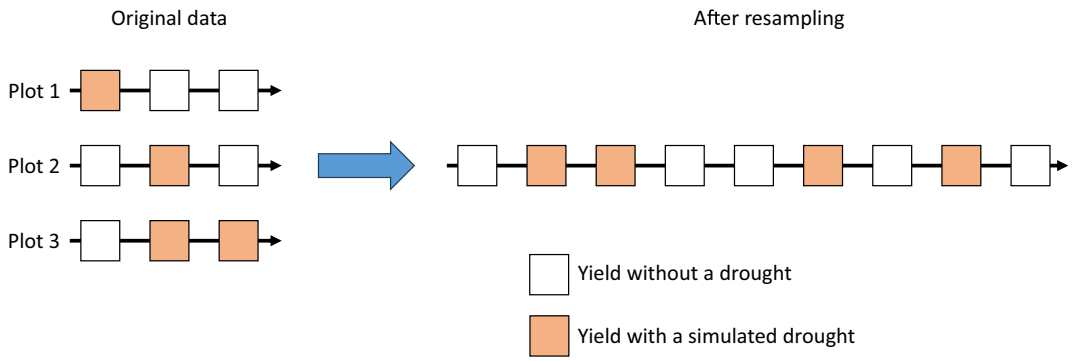

Fig. 3. Resampling strategy.
Note: Description of how the resampling strategy works. Yield values (with and without drought) are taken from different plots across limited number of years to simulate uncertainty for a single plot.

4.1.2. Economic insurance value

Second, reflecting eqs. (3) and (4) from the theoretical framework, we assess the economic importance of the derived effects, by evaluating the total insurance value of diversity $totIV_d(n)$ for different drought risk exposure d (Di Falco and Chavas, 2009):

$$totIV_d(n) = \int_{n_0}^{n} \left(-\frac{\partial RP}{\partial n} \right) dn = \int_{n_0}^{n} \left(-\frac{1}{2} r_2 P^2 \frac{\partial Var(y_d)}{\partial n} - \frac{1}{6} r_3 P^3 \frac{\partial Ske(y_d)}{\partial n} \right) dn \quad (20)$$

P is the price at which farmers could sell their forage production. We assume deterministic prices equal to 23 CHF per 100 kg (Farmers' Union, S., 2021). $\frac{\partial Var(y_d)}{\partial n}$ represents the effect of an increase in plant diversity on yield variance and $\frac{\partial Ske(y_d)}{\partial n}$ represents the effect of an increase in plant diversity on yield skewness. Note that $\frac{\partial Var(y_d)}{\partial n}$ is estimated by $\frac{\beta_{3,d}}{2\sqrt{n}}$ from the econometric model and $\frac{\partial Ske(y_d)}{\partial n}$ is estimated by $\frac{\beta_{5,d}}{2\sqrt{n}}$ from the econometric model. We consider a power utility function (see Section 2.1) and rather risk averse farmers with three possible coefficient of relative risk aversion: $\tau = 1$, $\tau = 1.5$ and $\tau = 2$ (Hardaker et al., 2015). We evaluate the insurance value under constant absolute risk aversion (CARA)[12] where the coefficients of absolute risk aversion r_2 and r_3 are constant across drought risk exposures[13].

4.2. Mechanisms

In this section, we describe our empirical strategies to investigate the mechanisms underlying the effect of diversity on the variance and skewness of yield (see Fig. 2.b.1 and 2.b.2).

4.2.1. Species interaction effect vs statistical averaging effect

So far, we estimate the total effect of plant diversity (i.e., the species interaction effect plus the statistical averaging effect) on the risk premium. Reflecting the theoretical framework and specifically the decomposition made in equation eqs. (8), (9) and (10), we want to understand the relative strengths of the species interaction and the statistical averaging effect on the risk premium (see Fig. 2b.1). The empirical approach relaxes the assumption of the theoretical framework regarding the yield distribution of individual plant species and their response to drought. To study these effects empirically, we consider a baseline setup where plant species can interact (i.e., different species within one field; setup so far in our analysis) vs. where they cannot directly interact (i.e., one species per field but several fields)[14], as illustrated in Fig. 4. Thus, for any given level of diversity, a difference in an outcome measure between the two setups is due the species interaction effect, as setup one contains both effects, but setup two only the statistical averaging effect. To conduct the analysis of the second setup, we generate yield data by randomly sampling and combining monoculture data so to obtain the same diversity levels (i.e., Shannon indices: 0, 0.69, 0.74, 1.39) and the same levels of drought risk exposures as for setup one.

4.2.2. Asynchrony and controlled direct effect analysis

So far, we did not factor in the varying complementarity among species as we solely focused on increasing diversity (i.e., Shannon index) to provide insurance value. However, farmers can use their knowledge on complementarity to cope with the drought risk. Therefore, we consider in this part the community asynchrony variable to estimate the complementarity between species. Community asynchrony is calculated based on the yield variation across harvests within a year (see eq. (11)). The inclusion of this variable allows us to isolate the effect of diversity unrelated to the increase in asynchronous responses, and thus determine the importance of complementarity (functional diversity) in deriving insurance value (see Fig. 2b.2). This distinction was not made in the theoretical framework because the model did not allow for it.

To test this, we conduct a direct effect analysis (Acharya et al., 2016) with community asynchrony as the mediator variable. Specifically, we estimate the following three equations (see Acharya et al., 2016; Bellemare et al., 2021 for further information about the implementation):

$$y_{i,d} = \alpha_{1,d} + \beta_{1,d} n_i^{0.5} + \gamma X^{Post} + \delta M + e_{1,i,d} \quad (21)$$

$$\widetilde{y_{i,d}} = y_{i,d} - \hat{\gamma} X^{Post} - \hat{\delta} M \quad (22)$$

$$\widetilde{y_{i,d}} = \alpha_{4,d} + \beta_{4,d} n_i^{0.5} + e_{4,i,d} \quad (23)$$

where X^{Post} represent control variables that are determined after the treatment is assigned, also called intermediate cofounders. We classify site and year dummy variables as intermediate cofounders because i) our treatment is highly exogenous (sown Shannon index), thereby requiring all cofounders to be classified as intermediate cofounders, and ii) site and year serve to account for divergent developments that occur after the treatment (sown Shannon index). M is the community asynchrony variable functioning as the mediator variable. This method allows us to

[12] We also test under constant relative risk aversion (CRRA, see supplementary material 2).
[13] We use the mean income under low drought risk exposure as $E(\pi)$ to compute the coefficients r_2 and r_3.
[14] For both those analyses we consider the same scale (per hectare) to allow the comparison between the two diversity gradients. For this purpose, diversity across fields (within a system) is simulated by taking shares from Monocultures directly representing the different mixtures (see Data section for the different mixtures).

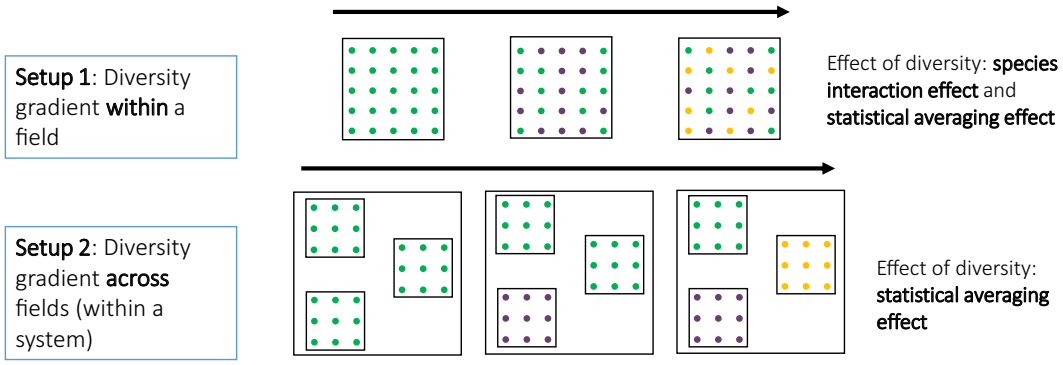

Fig. 4. Diversity gradients.
Note: Description of two different plant diversity gradients: diversity within a field and diversity across fields within a system. Ecological interactions between species are only possible in the case of diversity within a field.

estimate $\beta_{4,d}$, which denotes the direct effect of diversity on biomass yield, independently of the indirect effect of diversity on yield resulting from the increase in species asynchrony.

For the estimation of the controlled direct effect on the variance and skewness of yield, we estimate these moments by using the controlled direct effect error term $e_{4,i,d}$ such that $Var\left(y_{i,d}\right) = e^2_{4,i,d}$ and $Ske\left(y_{i,d}\right) = e^3_{4,i,d}$. We then apply the same methodology used to estimate the controlled direct effect on yield (see eqs. (21) (22) (23)).

5. Results

5.1. Insurance value

We find that the farmers' risk premium decreases with increasing plant diversity in all drought risk exposure scenarios, meaning that the total insurance value is increasing with increased plant diversity (Fig. 5 shows the total insurance value under three drought risk exposures for farmers exhibiting constant absolute risk aversion; we use the econometric results from the baseline scenario presented in supplementary material 3 to estimate the insurance value). For instance, under high drought risk exposure and relative risk aversion $\tau = 2$ (violet full line), the total insurance value of the most diverse mixture studied (Shannon index = 1.39) is equal to about 44 (±26) CHF per hectare, where the "±" indicates the bootstrap standard error. This constitutes a decrease in the risk premium of 37 % compared to the average risk premium for monoculture under high drought risk exposure of 118 CHF per hectare. The total insurance value remains largely unchanged under increasing drought risk exposure, although the level of total insurance value under high drought risk exposure (violet line) is slightly, but not significantly, higher than under no (blue) and low (green) drought risk exposure. It is worth noting that when drought risk exposure increases, i) the annual

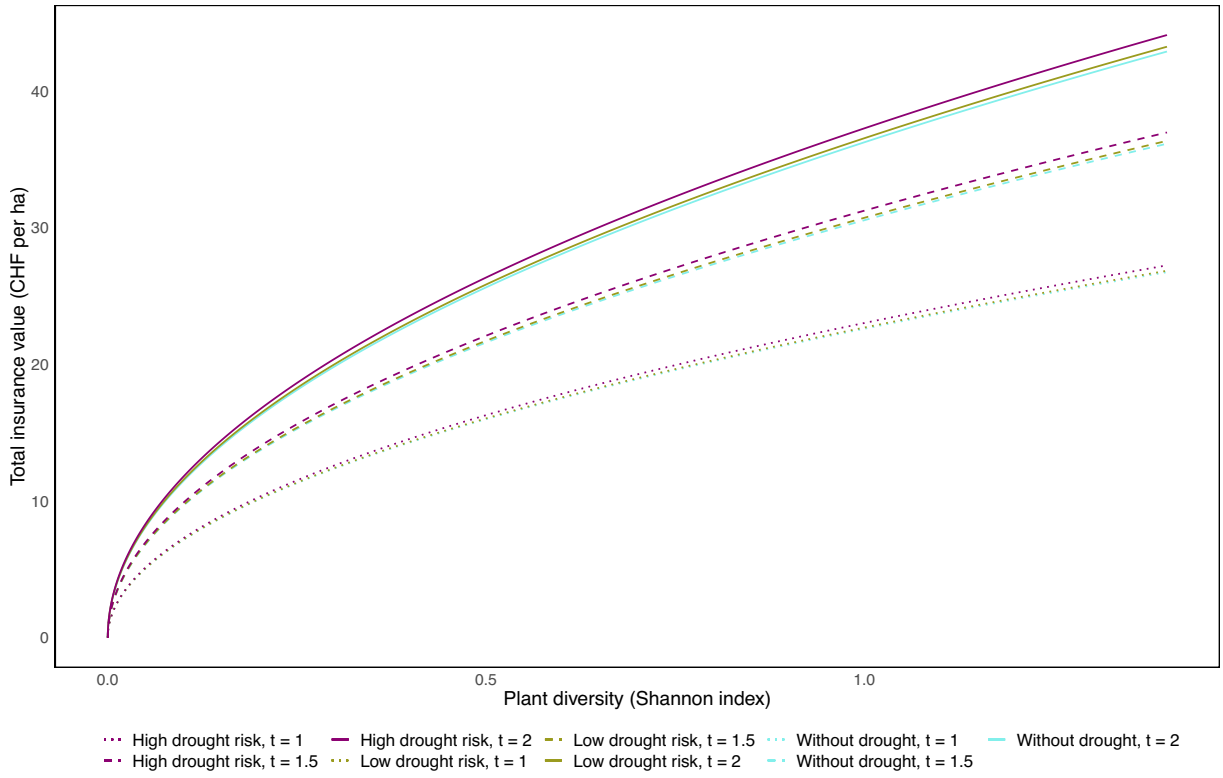

Fig. 5. Total insurance value of plant diversity under constant absolute risk aversion.
Note: Total insurance value for risk averse farmers exhibiting constant absolute risk aversion ($r = 1$, $r = 1.5$ and $r = 2$) under different drought risk exposure (without = blue, low = green and high = violet).

variance increases only marginally (in ton^2/ha^2, 4.98 without drought, 5.05 under low drought risk and 5.04 under high drought risk), ii) the skewness increases (in ton^3/ha^3, 0.58 without drought, 1.37 under low drought risk and 2.11 under high drought risk), and iii) the risk premium (including both variance and skewness effect) remains constant (in CHF per hectare 92 without drought, 92 under low drought risk and 91 under high drought risk) (see supplementary material 5 for more details).

5.2. Mechanisms

5.2.1. Species interaction effect vs. statistical averaging effect

In this sub-section, we disentangle the variance vs. skewness effects and species interaction vs. statistical averaging effects on the total insurance value. The analysis shows that plant diversity within a field reduces yield variance under all drought risk exposure scenarios (without, low and high) (see Fig. 6, all effects are significant at a 1 % level). The effect of diversity on yield variance does not change when drought risk exposure increases. For instance, under high drought risk exposure and while looking at diversity within a field, an increase of one root unit of plant diversity (Shannon index) leads to a decrease of yield variance of 3.40 (±1.17) on average (in ton^2/ha^2). Considering that average yield variance under high drought risk exposure is at 4.99, the decrease of variance is of relevant magnitude. This implies that yield variance is reduced by an increase in diversity, thus reducing risk for farmers. Regarding the comparison between the two diversity gradients (within a field and across fields), we find that the effect of diversity is higher (in absolute terms) for the gradient across fields, but not significantly different. This indicates that, for the variance reducing effect of diversity, the statistical averaging effect is the main driver and that the species interaction effect tends to decrease the total diversity effect, which supports the finding of the theoretical framework (see eqs. (9) and (10)).

Then, the analysis shows that plant diversity within a field reduces yield skewness under all drought risk exposure scenarios (see Fig. 7, all effects are significant at a 1 % level). The effect of diversity on yield skewness does not change when drought risk exposure increases. For instance, under high drought risk exposure and while considering diversity within a field, an increase of one root unit of plant diversity (Shannon index) leads to a decrease of yield skewness of 17.32 (±3.59) on average (in ton^3/ha^3). This implies that yield skewness is reduced (i.e. more negative) by an increase in diversity, thus increasing downside risk for farmers. Regarding the comparison between the two diversity gradients (within fields and across fields), we find that that the effect of diversity is lower (in absolute terms) for the diversity gradient across fields and significantly different at 1 % level (see Table 2 in supplementary material 3). This indicates that, for the skewness part, the statistical averaging effect is the main driver of the total diversity effect and that the species interaction effect tends to decrease the total diversity effect.

5.3. Asynchrony and controlled direct effect analysis

In this sub-section, we report whether asynchrony mediates the effect of diversity on variance and skewness (see Figs. 6 and 7). We find that the stabilizing effect of plant diversity on variance is (almost) completely mediated by asynchrony, as the direct effect of diversity is close to zero (−0.44 (±1.84)). In contrast, the negative effect of plant diversity on skewness is not mediated by asynchrony as the estimated effect is −14.41 (±6.72; significant at a 5 % level) compared to the total effect of 17.32 (±3.59).

5.4. Minimum detectable effect size analysis

Given the sample size ($N = 206$) and that we assess different moments of the distribution (variance and skewness), we may face limited statistical power for identifying small effects (i.e., a Type 2 error for them). To address this, we conduct a minimum detectable effect size analysis (Bloom, 1995; see supplementary material 9 for details). The results indicate that, while we cannot fully rule out the possibility of missing smaller but meaningful effects, the minimum detectable effect size analysis does not suggest a major risk of Type 2 errors for the estimation of coefficients shown in Figs. 6 and 7.

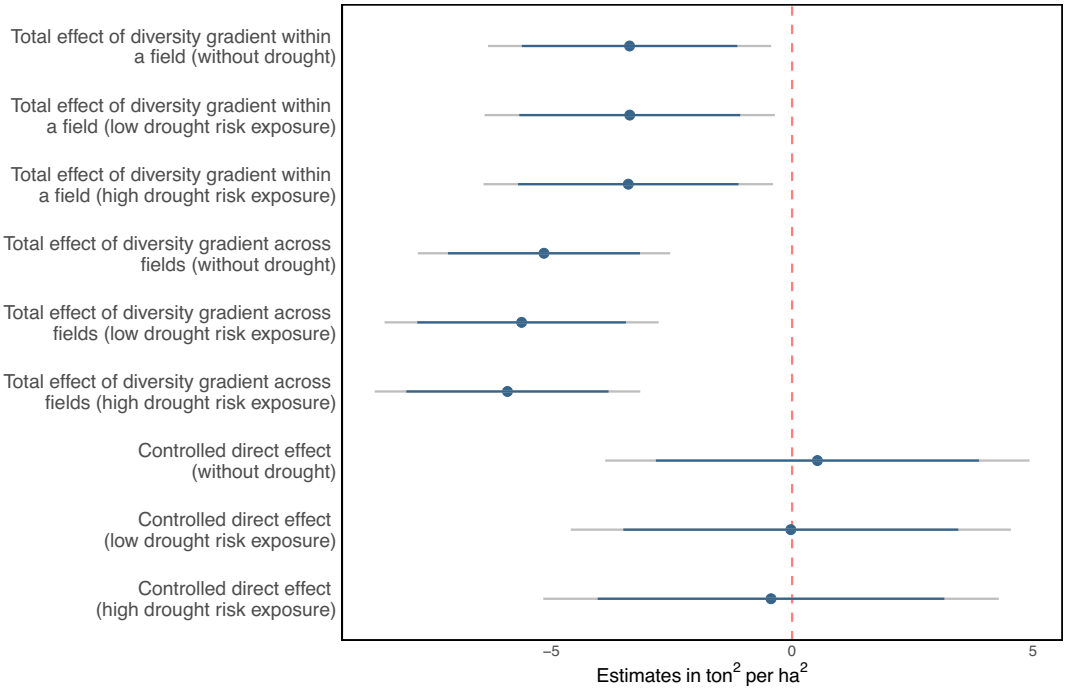

Fig. 6. Plant diversity effect on yield variance.
Note: Econometric results from eq. (18). The following effects per root unit of plant diversity are shown for without, low and high drought risk exposure: i) the total effect of diversity within a field on yield variance (baseline scenario), ii) the total effect of diversity across fields on yield variance (see Fig. 4) and iii) the controlled direct effect of diversity on yield variance independently of community asynchrony. Error lines are 95 % (blue) and 99 % (grey) confidence intervals.

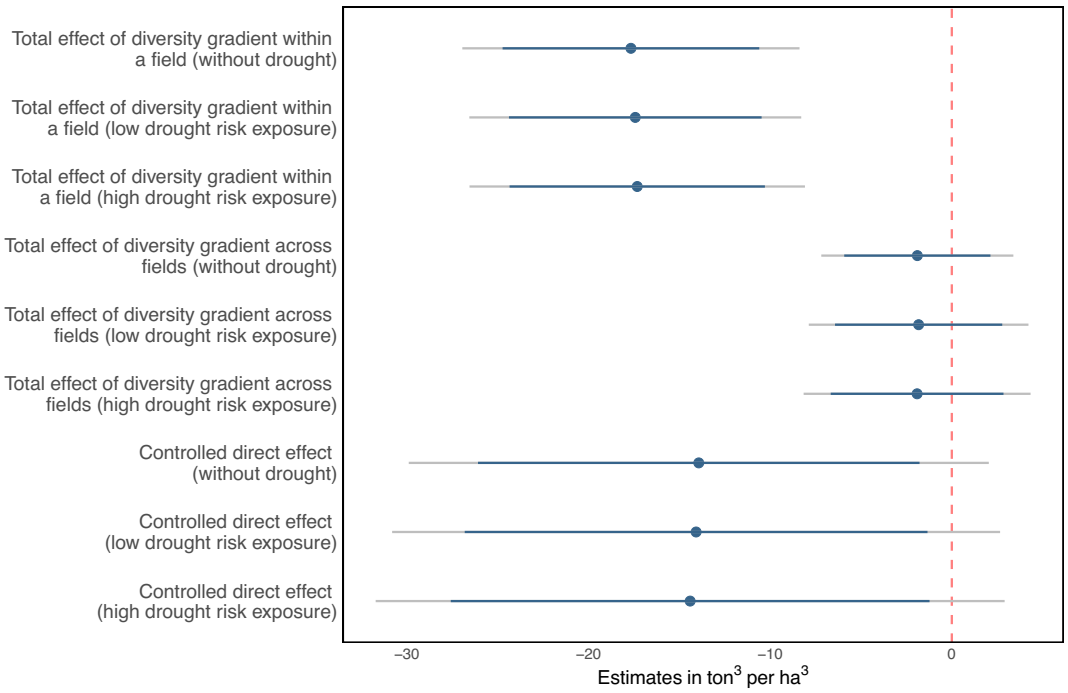

Fig. 7. Plant diversity effect on yield skewness.
Note: Econometric results from eq. (19). The following effects per root unit of plant diversity are shown for without, low and high drought risk exposure: i) the total effect of diversity within a field on yield skewness (baseline scenario), ii) the total effect of diversity across fields on yield skewness (see Fig. 4) and iii) the controlled direct effect of diversity on yield skewness independently of community asynchrony. Error lines are 95 % (blue) and 99 % (grey) confidence intervals.

6. Conclusion

We present a new theoretical and empirical analysis of the potential plant diversity can have as a natural insurance when drought risk increases. We consider both risk and downside risk and explore different mechanisms underlying the insurance value of diversity. Our stylized theoretical framework investigates production-oriented ecosystems and describes the insurance value of diversification strategies through a portfolio perspective. Our empirical evidence, based on three site-years of grassland experiments in Switzerland, shows that sown plant diversity provides consistent insurance value even under higher level of drought risk exposure. Moreover, we show that modest plant diversity can offset a large portion (37 %) of the risk premium of farmers. Additionally, we highlight the key role that community asynchrony plays in the risk reducing effect associated with diversity.

Our analysis has implications for farmers and policymakers. Encouraging the use of plant diversity at low richness levels (e.g., up to four to six species) as a form of natural insurance in sown productive grasslands can create a win-win situation by reducing risk for farmers as well as increasing other ecosystem services, i.e., public welfare that is not considered in this paper (Huber et al., 2022; Suter et al., 2021). To effectively use the natural insurance properties of plant diversity, farmers, extension services, and policymakers should consider sowing and maintaining diversity that maximizes the complementarity of plant species in the field, e.g., by sowing mixtures of productive species from different functional groups (e.g., grasses, legumes, herbs; Grange et al., 2021; Lüscher et al., 2022). Furthermore, given the beneficial effect of sown plant diversity, both privately and publicly[15], it might be valuable in regions with low adoption rates to increase adoption through information campaigns aimed at raising farmers' awareness of the benefits of this approach (Binder et al., 2018).

Our analysis has implications for future research. We have used here an ex-ante approach that seeks to simulate yield variance and skewness by analyzing experimental data, enabling us to identify the causal effect of plant diversity on yield variability. Given that our empirical study focused on Swiss agro-climatic conditions, the magnitude of the effect in other countries may vary (Anderson et al., 2023). Nevertheless, we expect the direction of the results to be the same for other European countries because of generally positive diversity effects on yield in productive grasslands across Europe (Finn et al., 2013) and because a risk reducing mechanism as shown here has often been found (Finger and Buchmann, 2015; Schaub et al., 2020a, 2020b). Moreover, we show that the insurance value of plant diversity in grasslands is mainly driven by statistical averaging between yields of individual species, while the ecological interactions between these species tend to reduce this value. This is important for research using model-based grassland data, as failing to account for plant species interactions could lead to an overestimation of the insurance value of plant diversity. The use of observational data could widen the spatial coverage of our analysis; however, such data would likely lead to endogeneity issues (e.g., due to pedoclimatic conditions affecting the choice of sown plant diversity by farmers). In addition, alternative approaches could be explored to model the distribution of yield, incorporating higher moments of the distribution—for example, through the use of quantile autoregressive models (e.g., Chavas et al., 2022). Moreover, as we focus solely on production risk, future work could consider market risks, such as price volatility, to extend our work and deepen the understanding of plant diversity as a risk management instrument. Furthermore, this analysis sets the base for future research extension on the interrelation of formal insurance systems and their subsidization and the use of natural insurance. Depending on how they interact (i.e., substitutes or complements) and the principal grassland production system in a country (sown monocultures or a well-developed mixture system), subsidizing formal insurance may disincentivize the use of natural insurance through increasing species diversity, leading to adverse effect on public welfare. Consequently, this could hinder the development of sustainable food

[15] Public benefits were not investigated in our study but have been demonstrated in previous research (e.g., Scheper et al., 2023).

production systems.

Funding declaration

We hereby confirm that this study is original and acknowledge the support from the Swiss National Science Foundation, under the project 'InsuranceGrass' No. 200918.

Data and code availability

The data used for the empirical part of this paper are openly available at https://doi.org/10.3929/ethz-c-000786416. The coding was done with the software R and the code is available in the supplementary material.

CRediT authorship contribution statement

Nicolas Alou: Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Sergei Schaub:** Writing – review & editing, Methodology, Conceptualization. **Matthias Suter:** Writing – review & editing, Data curation. **Andreas Lüscher:** Writing – review & editing, Data curation. **Robert Finger:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

All authors declare that they have no significant competing financial, professional, or personal interests that might have influenced the performance or presentation of the work described in this manuscript.

Appendix A. Supplementary data

Supplementary material to this article can be found online at https://doi.org/10.1016/j.ecolecon.2025.108852.

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