Plant diversity to cope with increased drought risk in grasslands

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Abstract

Grasslands are essential for the global milk and meat production and for the provision of other crucial ecosystem services. With climate change and the increased likelihood of extreme weather events, the stability of the provision of those ecosystem services is expected to decrease. In this paper, we study theoretically and empirically how plant diversity can function as a natural insurance under different drought risk exposures in grassland. The theoretical framework, which uses a portfolio perspective to describe plant diversity and uses community asynchrony as an indicator of complementarity between species, shows how plant diversity may provide insurance value against increased drought risk. Our empirical findings suggest that for a risk averse decision maker, accounting for risk (variance) and downside risk (skewness), plant diversity has a negative effect on risk premium, demonstrating that plant diversity does offer insurance value. Furthermore, our analysis reveals that this effect remains consistent even under higher levels of drought risk exposure. The results are relevant to both policy and industry, as plant diversity can provide a sustainable adaptation to climate change and complement or substitute traditional financial insurance against droughts.

Keywords Plant diversity, drought, insurance value, risk, biodiversity

JEL code Land Ownership and Tenure; Land Reform; Land Use; Irrigation; Agriculture and Environment Q150, Valuation of Environmental Effects Q510, Ecological Economics: Ecosystem Services; Biodiversity Conservation; Bioeconomics; Industrial Ecology Q570

1. Introduction

Grasslands are the backbone of food production globally as they cover more than 60% of all agricultural lands (FAO, 2021). Grasslands provide a wide range of ecosystem services and thus are of large policy relevance (Huber et al., 2022; Lopez et al., 2022). Climate change and increasing occurrence of extreme weather events threaten agriculture and grassland based farming systems, often resulting in lower and more variable yields for farmers (Orlowsky & Seneviratne, 2012). Grasslands are affected by extreme weather events, for example, as they are mainly rainfed (De Boeck et al., 2016; Gilgen & Buchmann, 2009; Vogel et al., 2012). To increase the economic resilience and reduce the risk from such events, farmers can use various risk management strategies on their fields and farms. Especially natural insurance strategies that rely on species interactions and species differences (i.e., asynchrony) to stabilize yields are relevant. 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 (Isbell et al., 2011). The importance of such natural insurances is exacerbated as financial insurances against extreme weather events in grasslands are often not well represented (Meuwissen et al., 2018; Vroege et al., 2019). Understanding the role that plant diversity can play in buffering yield losses from droughts is therefore key to creating sustainable food production systems (Tilman et al., 1996).

We study the economic potential of natural insurance (i.e., plant diversity) for grassland-based farming systems under increasing drought risk. To this end, natural insurance properties are derived by considering plant diversity as portfolio of plants and drought risk exposure as increasing farmers' income risk (i.e., the temporal variability and skewness of income). First, we analysis these relationships using a theoretical setup and, second, we use an empirical application to quantify the impact of plant diversity on the variability of yields to derive the insurance value of plant diversity under different drought risk exposure and risk preferences.

A large number of ecological studies have addressed the effect of plant diversity on grassland production and stability. This interaction consists of two main mechanisms. First, the mean production often increases with a higher diversity of plants due to various effects (Finn et al., 2013a; Marquard et al., 2009; Nyfeler et al., 2009; Tilman et al., 1996). Second, higher plant diversity has been shown to increase the overall stability of biomass production (Isbell et al., 2009; Loreau et al., 2021). In fact, two different effects from diversity on variability can be distinguished. First, derived from functional diversity in the field, ecological interaction between species stabilize ecosystem functions due to complementarity between species (Hallett et al., 2017). Second, due to differences in responses to environmental pressures by species, biomass production can also be stabilized from a purely statistical ground[1] (Koellner & Schmitz, 2006). Furthermore, various recent studies have conducted economic analysis of biodiversity in grassland farming system (Baumgärtner, 2008; Baumgärtner & Quaas, 2010; Finger & Buchmann, 2015; Schaub, Finger, et al., 2020). As a result, plant diversity appears to increase the economic value of grasslands through an increase in the mean of income and, for risk averse decision makers, also due to a decrease in the variability of income (Schaub, Buchmann, et al., 2020). However, high plant diversity is often also more costly to achieve (Schaub et al., 2021; Török et al., 2011). A small portion of the literature also studied diversity through a portfolio perspective to infer profitability from species richness (Binder et al., 2018; Koellner & Schmitz, 2006). In this context, species considered as assets make up

[1]Here the purely statistical effect refers the change in variance of overall biomass production caused by imperfect correlations between the biomass productions of the different individual species.

the farmer's portfolio. Additionally, in past ecological studies, a community synchrony variable was developed to explore the synergies among species in communities with multiple species (Loreau & de Mazancourt, 2008). This variable, which is based on the differences between individual species' variances, quantifies the extent to which the temporal responses of different species complement each other within a community. In fact, in the agricultural context, asynchrony may serve as a fundamental property of diversity to explain the effect of diversity on yield stability (Egli et al., 2020).

To assess the potential of diversity as natural insurance against increased drought risk exposure it is key to understand the effect of plant diversity on drought resistance[2]. The ecological literature on the effect of plant diversity on drought resistance provides mixed results. First, a share of the literature find a positive effect of diversity on drought resistance (Hofer et al., 2016; Isbell et al., 2015). Second, some studies find that the effect of diversity remains significant under drought conditions but find no significant differences between the drought losses for different levels of diversity (Grange et al., 2021). Third, a last share of the literature finds that diversity can actually decrease the resistance against drought such that drought losses would increase in the case of higher diversity (Pfisterer & Schmid, 2002; Van Ruijven & Berendse, 2010). On the one hand, the positive impact of biodiversity on the overall mean and stability of yields persists under droughts conditions (Haughey et al., 2018; Hofer et al., 2016; Isbell et al., 2015). On the other hand, plant diversity shows no impact or a negative impact on drought resistance (Pfisterer & Schmid, 2002; Van Ruijven & Berendse, 2010). Plant diversity appears to have a negligible impact against droughts compared to other management practices such as mowing frequency (Vogel et al., 2012).

In light of previous research, we aim to contribute to economic literature by exploring a novel approach to deriving natural insurance properties (insurance value) from plant diversity in grassland-based production systems against droughts. More specifically, we conduct an economic analysis using a portfolio perspective for plant diversity in order to capture risk-reducing mechanisms. Our contribution is three-fold. First, we model if and how an increase in drought risk leads to a higher optimal level of plant diversity and how it successfully functions as a natural insurance using a portfolio perspective and certainty equivalent theory. Additionally, to account for different complementarities between species, we include the community synchrony variable in our theoretical framework, which is a novel feature for economic literature. Second, we empirically examine if and how an increase in the number of plants can reduce production risks, especially also accounting for downside risks. To do so we quantify the impact of diversity on yield variability and skewness and we derive the insurance value from diversity under different drought risk exposures. Finally, we investigate theoretically and empirically the relative importance of the different mechanisms driving this insurance value (i.e., ecological interaction between species vs statistical effect derived from imperfect correlations between species) (Koellner & Schmitz, 2006).

Our main results suggest that plant diversity reduces the risk for farmers by decreasing yield variance, but at the same time increases the downside risk by decreasing yield skewness. The net effect on farmers' risk premium is negative, demonstrating that plant diversity offers insurance value. Moreover, the findings remain constant even under higher levels of drought risk exposure, thus showing the potential of plant diversity as risk management instrument

[2] The concept of drought resistance refers to the proximity of production under normal conditions and dry conditions. For instance, a decrease of one-third in production under dry conditions would imply greater drought resistance than a decrease of half the production (Isbell et al., 2015).

under more risky conditions. Finally, the statistical effect is determined to be the primary contributor to the insurance value, rather than the ecological effect.

The remainder of the paper is organized as follows. First, we model farmers' choice of diversity and natural insurance mechanisms. Next, we quantify the impact of diversity on production under different risk exposures. Finally, we discuss and present our conclusions.

2. Theoretical frameworks

2.1 Model

In this section, we develop a theoretical economic model to study the insurance value of plant diversity in temporary productive grasslands. The model includes a novel portfolio approach to describe plant diversity as drought insurance. In our model, livestock are either fed by harvested grass or directly grass to produce milk and meat. In turn, farmers generate income directly by selling produced milk and indirectly through grassland yields. We consider the dry matter yield variable $DM\ Y_i$ to describe the biomass fed to livestock. To estimate milk production, we define the milk production potential from dry matter yields MPP_i. The profit of farmers is defined as follows:

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

where π represents the profit of farmers. P_m is the milk price. l_i is the share of species i in the fields. $Y_i(n, d)$ is the quality corrected yields of species i expressed in kg ha^{-1} such that $\widehat{Y_i} = DM\ Y_i \times MPP_i$. This allows a direct link between the dry matter yields and milk production. $\sum_{i=1}^{n} l_i Y_i(n, d)$ is the portfolio of the different plant species. $c(n)$ is the part of the farmer's cost of production related to species diversity. This cost is increasing in n meaning that a higher diversity is more costly for farmers (Schaub et al., 2021). We assume farmers maximize their utility by choosing the number of species n planted in their fields. $C(x)$ is the cost of production unrelated to species diversity, where x represents all the other management factors. Drought risk is modeled via variable d describing the perceived frequency of severe summer droughts across recent years. A summer is considered to have suffered a severe drought when the standardized precipitation evapotranspiration index (SPEI) has crossed the threshold of -1.5 (Vicente-Serrano et al., 2010; Yu et al., 2014). Such level of a SPEI indicates that water availability for grasslands is reduced[3]. Therefore, a higher frequency of summer with such levels of SPEI leads to higher production risks. Both n and d affect the different yields of the different species. n affects the different yield means through various mechanisms (Schaub, Buchmann, et al., 2020) and d decreases the different yield means (Finger et al., 2013; Gilgen & Buchmann, 2009).

In this model, to be able to express diversity as a function of n all grasslands species are assumed to have identical yields $\widehat{Y_i}(n, d) = \widehat{Y_F}(n, d)$. This assumption is fair for our framework since we look into the insurance value of species diversity thus neglecting the mean effect. Therefore, the profit can now be described as the following:

$$\pi = P_m \widehat{Y_F}(n, d) - c(n) - C(x) \tag{2}$$

[3] A negative level of SPEI means that atmospheric water supply derived from precipitation is inferior to atmospheric water demand (Bucheli et al., 2021)

P_m, $c(n)$ and $C(x)$ are assumed to be deterministic and not affected by droughts[4]. $\widehat{Y_F}(n,d)$ is assumed stochastic. In order to describe the profit variance as a function of n, we assume that all plants have the same yield variance $\sigma^2(n,d)$ and that their variance is affected identically by drought risk and by plant diversity. Substantial differences in individual species variances may lead to one species with low variance dominating other more diverse portfolios. However, this is unlikely to be the case, as stability is higher in diversified grasslands, with or without climatic perturbation (Haughey et al., 2018; Isbell et al., 2015; Schaub, Buchmann, et al., 2020). Furthermore, the impact of differences in species variance relative to the impact of correlation terms on community variance will decrease with greater diversity, since the addition of a species results in the addition of $n(n-1)$ covariance terms and only n variance terms (Loreau & de Mazancourt, 2008).

We here assume grassland production systems where diversity is mainly controlled by seeding[5]. We assume that each plant has an equal share in the field since ecological interactions are higher under uniformity of species abundance (Kirwan et al., 2007). The variance of income can therefore be described as follows (Robison & Barry, 1987):

$$var(\pi) = {P_m}^2 \frac{1}{n}(1 + (n-1)\rho)\sigma^2(n,d) \tag{3}$$

Where ρ represent the average correlation between species such that: $\rho = \frac{1}{n(n-1)}\sum_{i=1}^{n}\sum_{j\neq 1}^{n}\rho_{ij}$. We assume that drought risk d do not impact the correlation between species (Muraina et al., 2021). Drought risk d affects the variance of income through its impact on the variance of individual species yields. Plant diversity n affects the income through two channels. First, it impacts the variance of income through its impact on individual species yield due to ecological interactions between species. Second, it impacts the variance of income mechanically depending on the average correlation due to the portfolio framework.

2.2 Risk premium and insurance value[6]

To describe utility of farmers we consider power utility function (Finger et al., 2013):

$$U = (\frac{1}{1-\tau})\pi^{1-\tau} \tag{4}$$

We assume that farmers are risk averse, thus the absolute Arrow Pratt coefficient of risk aversion r, is defined as $r = -U''/U' = \tau/E(\pi) > 0$ (Iyer et al., 2020).
Maximizing the expected utility is equivalent to maximizing the certainty equivalent. The risk incurred by farmers is captured by the risk premium (Chavas, 2004). The risk premium can be approximated by: $RP = \frac{1}{2}r{\sigma_\pi}^2$ (Pratt, 1964). Therefore, we obtain:

[4] We assume that costs depends mostly on management decision (e.g., fertilizer input, number of cuts, sown mixtures). Moreover, we assume that farmers may use other feed sources than grass such that shortage in grass due to drought may not affect the hay prices.
[5] 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.
[6] In a next phase for the paper, the effect of diversity through skewness will be included in the theoretical part of the paper.

$$RP = \frac{1}{2} r {P_m}^2 \frac{1}{n} (1 + (n-1)\rho) \sigma^2(n,d)^7 \tag{5}$$

In the following, we evaluate the first derivative with respect to drought risk d and the number of species n.

Drought risk d:

$$\frac{\partial RP}{\partial d} = \frac{1}{2} r {P_m}^2 \frac{1}{n} (1 + (n-1)\rho) \frac{\partial \sigma^2(n,d)}{\partial d} > 0 \tag{6}$$

An increase in drought risk increases the risk premium due to the increase in species variances such that: $\frac{1}{2} r {P_m}^2 \frac{1}{n} (1 + (n-1)\rho) \frac{\partial \sigma^2(n,d)}{\partial d} > 0$. This is a fair assessment since yield stability decreases during droughts[8] (Haughey et al., 2018; Muraina et al., 2021) (also Schaub et al (in preparation)). Moreover, the increased drought risk will lead to an increase in the frequency of lower yield extremes, which will increase the standard deviation of yields and thus the variance of profits. Finally, the certainty equivalent decreases with an increase in drought risk, thus leading to a lower expected utility for farmers.

Diversity of plants n:

$$\frac{\partial RP}{\partial n} = -\frac{1}{2} r {P_m}^2 \frac{1}{n^2} (1-\rho) \sigma^2(n,d) + {P_m}^2 \frac{1}{n} (1 + (n-1)\rho) \frac{\partial \sigma^2(n,d)}{\partial n} \tag{7}$$

The risk premium is affected through two different mechanisms when plant diversity n increases. First, as long as the average correlation between species ρ is smaller than +1, i.e., there are some potential gains of diversification, the following is implied:

$$-\frac{1}{2} r {P_m}^2 \frac{1}{n^2} (1-\rho) \sigma^2(n,d) < 0 \tag{8}$$

Equation (8) refers to the first part of equation (7) in red. This means that an increase in n would decrease the risk premium and increase the certainty equivalent. This represents the statistical effect derived from imperfect correlations between species.
Second, according to previous literature more diversity in a field reduces individual species variances such that: $\frac{\partial \sigma^2(n,d)}{\partial n} < 0$ (Hallett et al., 2017), thus implying:

$${P_m}^2 \frac{1}{n} (1 + (n-1)\rho) \frac{\partial \sigma^2(n,d)}{\partial n} < 0 \tag{9}$$

Equation (9) refers to the second part of equation (7) in green. This represents the ecological effect derived from ecological interaction between species on risk/variance.

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[7] In this framework, we the downside risk part of the risk premium is not considered as we focus on risk. Downside risks are investigated in the empirical analysis where the skewness of yield is analyzed.
[8] Related work studies the effect of drought on grassland stability (Schaub et al., in preparation).

To describe the effect of diversity on the certainty equivalent through the risk premium we use the insurance value IV of species richness. It shows by how much the risk premium decreases when richness increases. It takes the following form[9] (Baumgärtner, 2008; Finger & Buchmann, 2015):

$$IV(n) = -\frac{\partial RP}{\partial n} = \frac{1}{2} r {P_m}^2 \frac{1}{n^2}(1-\rho)\sigma^2(n,d) - {P_m}^2 \frac{1}{n}(1+(n-1)\rho)\frac{\partial \sigma^2(n,d)}{\partial n} \quad (10)$$

In this paper, we investigate how the insurance value changes when drought risk increases. For this purpose, we derive the following equation describing the change in insurance value with respect to drought risk:

$$\frac{\partial IV(n)}{\partial d} = -\frac{\partial^2 RP}{\partial n \partial d} = \frac{1}{2} r {P_m}^2 \frac{1}{n^2}(1-\rho)\frac{\partial \sigma^2(d)}{\partial d} - \frac{1}{2} r {P_m}^2 \frac{1}{n}(1+(n-1)\rho)\frac{\partial \sigma^2(n,d)}{\partial n \partial d} \quad (11)$$

The changes in insurance value of plant diversity with respect to increased drought risk is composed of two terms. First, $\frac{1}{2} r {P_m}^2 \frac{1}{n^2}(1-\rho)\frac{\partial \sigma^2(d)}{\partial d}$ represents the statistical effect against an increase drought risk exposure. If $\frac{\partial \sigma^2(d)}{\partial d} > 0$ as assumed, the statistical effect will be positive as long as the average correlation between species ρ is smaller than +1[10]. This implies that the addition of a new species increases the insurance value more when drought risk are higher. Second, $-\frac{1}{2} r {P_m}^2 \frac{1}{n}(1+(n-1)\rho)\frac{\partial \sigma^2(n,d)}{\partial n \partial d}$ represents the ecological effect against an increase in drought risk exposure. The key element for the ecological effect is the second derivative of individual species variance with respect to diversity and drought risk exposure $\frac{\partial \sigma^2(n,d)}{\partial n \partial d}$. From previous ecological literature we cannot conclude on the sign of the previously mentioned element, i.e. findings are ambiguous (Grange et al., 2021; Hofer et al., 2016). Therefore, the magnitude and sign of the ecological effect is unknown. These results show that the effect of plant diversity may increase the insurance value more under higher drought risk exposure through two different effects (i.e., statistical effect and ecological effect). Moreover, even when the ecological effect of plant diversity bears no effect or a negative effect on insurance value[11], greater plant diversity may still be a viable risk management strategy due to the statistical effect derived from temporal imperfect correlations between species.

The correlation between individual species yield is the key to the statistical effect on insurance value. Lower average correlation, that signal low plant community synchrony (Bjørnstad et al., 1999; Loreau & de Mazancourt, 2008), leads to higher insurance value for famers. The statistical effect on insurance value is expected higher for mixes with plant species coming from different functional groups (Lüscher et al., 2022). Thus, we expect diminishing effect for higher levels of diversity.

2.3 Synchrony variable and general model

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[9] Which is the negative of equation (6)

[10] We assume that the correlation of species of the same functional group is closer than across functional groups. Thus, we expect diminishing effect from diversity as more species are included (Lüscher et al., 2022).

[11] If $\frac{\partial \sigma^2(n,d)}{\partial n \partial d} \geq 0$

In recent ecological studies a new community synchrony measure has been used to describe complementarity between species both ecologically and statistically (Hautier et al., 2014; Loreau & de Mazancourt, 2008; Zhao et al., 2022):

$$\varphi = \frac{{\sigma_T}^2}{\left(\sum_{i=1}^{n} l_i \sigma_i\right)^2} \tag{12}$$

Where φ represent the community yield synchrony. ${\sigma_T}^2$ is the total yield variance in the field. $\sum_{i=1}^{n} l_i \sigma_i$ is the weighted average yield standard deviation. Ecological literature finds that synchrony (or asynchrony) is an important factor of yield stability with and without drought consideration (Haughey et al., 2018; Muraina et al., 2021; Sasaki et al., 2019).

Regarding this framework, plant community synchrony is used as a property of diversity to generalize the model and account for the complementarity between species and not only species richness. The variance of income is now described by the following equation:

$$var(\pi) = {P_m}^2 {\sigma_c}^2(n, d, \varphi) \tag{13}$$

Where ${\sigma_c}^2(n, d, \varphi)$, identified as the community variance, represents the total yield variance from all species in the field. The community variance varies with n, d and φ[12]. According to previous literature (Haughey et al., 2018), we define the effect of community synchrony as follows: $\partial {\sigma_c}^2 / \partial \varphi > 0$, meaning that community variance increases when synchrony increases. In other words, a more asynchronous plant community (i.e., a community where plant species are more complementary) leads to lower community variance and therefore a lower income variance.

The economic implication are described through the general insurance value IV of species richness and the change in insurance value with respect to drought risk:

$$IV(n) = -\frac{\partial RP}{\partial n} = -\frac{1}{2} r {P_m}^2 \frac{\partial {\sigma_c}^2(n, d, \varphi)}{\partial n} \tag{14}$$

$$\frac{\partial IV(n)}{\partial d} = -\frac{\partial^2 RP}{\partial n \partial d} = -\frac{1}{2} r {P_m}^2 \frac{\partial^2 {\sigma_c}^2(n, d, \varphi)}{\partial n \partial d} \tag{15}$$

The insurance value 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 2.2). The community synchrony variable is relevant for decision makers as it may affect the relation between plant diversity and community variance $\frac{\partial {\sigma_c}^2(n,d,\varphi)}{\partial n}$, and therefore also affect the insurance value of diversity $IV(n)$. From previous insight (Sasaki et al., 2019), we expect that under lower synchrony the effect of plant diversity on the variance may be higher (in absolute value). Thus, leading to higher insurance value for more asynchronous plant communities. The effect of synchrony on the change in insurance value with respect to drought is however undefined.

[12] $\partial {\sigma_c}^2 / \partial n < 0$ and $\partial {\sigma_c}^2 / \partial d > 0$ from previous framework.

3. Data

To conduct the analysis, we use annual yield data of three coordinated grassland experiments (two Swiss and one Irish site) representing intensively managed agricultural grasslands in Switzerland and Ireland (Haughey et al., 2018; Hofer et al., 2016).
The experiment included various levels of diversity. The plots were sown in four different monocultures (plant species = 1) and eleven different polycultures (plant species > 1), using four different species (two grasses and two legumes). The polycultures were sown using different number of species (i.e., either two or four) and different shares of the species (i.e., polyculture 1: 0.5, 0.5, 0, 0, polyculture 2: 0.79, 0.07, 0.07, 0.07, polyculture 3: 0.25, 0.25, 0.25, 0.25). Considering that four species were used for those polycultures, the experiment included six different compositions of polyculture 1, four different compositions of polyculture 2 and one composition of polyculture 3. We use the Shannon index[13] to describe the plant diversity of those plots (Shannon, 1948):

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

Thus, we obtain for the monocultures and the different polycultures four Shannon index levels: 0, 0.69, 0.74, 1.34.

Across the grassland plots at each site a summer drought experiment was conducted, meaning that a randomly selected half of the plots was covered for nine to ten weeks in the summer to simulate an extreme summer drought. Thus, each annual yield data observation has a variable indicating whether a drought was simulated (drought=1) or not (drought=0). In our analysis, drought risk exposures was defined by the shares of observations with a drought treatment in our sub samples. We simulate two drought frequency scenarios: 20% (low), 40% (high) (Schaub & Finger, 2020). For instance in a scenario with 20% of drought frequency, 80% of the observations selected into the sub sample are without drought treatment.

4. Empirical method

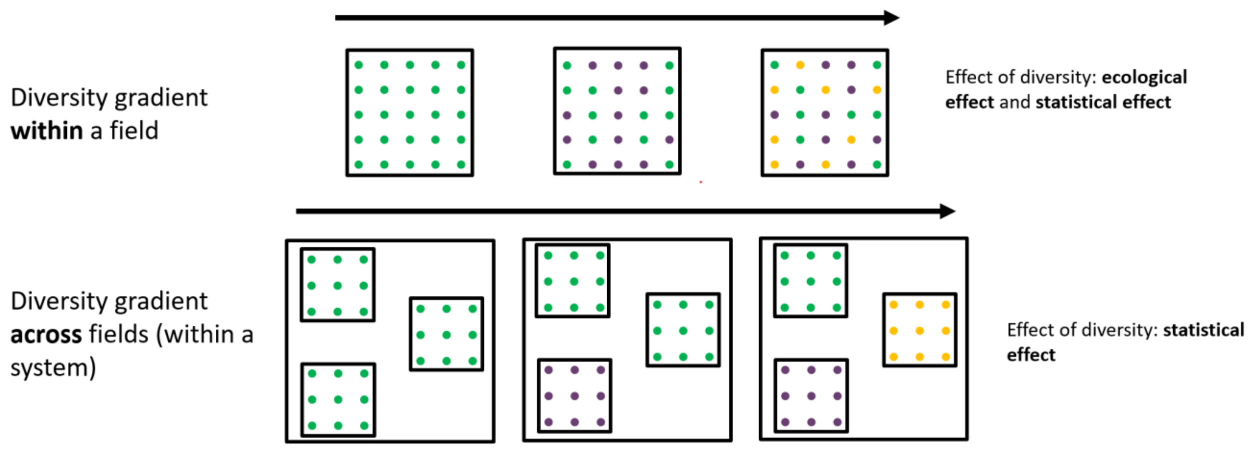
We conducted two ex-ante analyses to understand changes of the insurance value of diversity when drought frequency increases. In the first analysis we consider diversity within a plot, where plants can interact, and in the second we consider diversity within a system but not within a plot, thus, plants do not interact with each other[14] (Figure 1). These two analyses allow us to test whether i) the insurance value of diversity is higher, similar or lower when drought frequency increases and ii) ecological interaction between species or statistical effect due to temporal complementarity between species are responsible for (changes in the) insurance value. The test for ii) can be done by comparing the results from both analyses,

[13] Due to our low diversity gradient (up to 4 species) we use the Shannon index, as compare to the Simpson index, gives more weight to the richness vs the distribution of species.
[14] For both those analysis 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 monoculture directly representing the different polycultures (see Data section for the different polycultures).

since multiple monocultures will only be affected by the statistical effect and not by ecological interactions.

The first analysis is structured in two parts: 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.

Figure 1: Diversity gradients



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

Diversity effect on variance and skewness. To estimate the effect of plant diversity on variance and skewness, we use a stochastic production function method (Antle, 1983; Just & Pope, 1979):

$$y_{i,d} = \alpha_{1,d} + \beta_{1,d} n_i^{0.5} + \beta_{2,d} Site_i \times Year_i + e_{1,i,d} \tag{17}$$

$$Var(y_{i,d}) = e_{1,i,d}^2 \rightarrow Var(y_{i,d}) = \alpha_{2,d} + \beta_{3,d} n_i^{0.5} + \beta_{4,d} Site_i \times Year_i + e_{2,i,d} \tag{18}$$

$$Ske(y_{i,d}) = e_{1,i,d}^3 \rightarrow Ske(y_{i,d}) = \alpha_{3,d} + \beta_{5,d} n_i^{0.5} + \beta_{6,d} Site_i \times Year_i + e_{3,i,d} \tag{19}$$

Where $y_{i,d}$ represents biomass yield of observation i depending on the drought risk exposure d. n_i represents the plant diversity level modeled through the Shannon index and $Site_i \times Year_i$ are control dummies to account for differences between sites and year[15]. $Var(y_{i,d})$ and $Ske(y_{i,d})$ are estimated variance and skewness of yield for observation i depending on the drought risk exposure d estimated from the first stage regression. The diversity effect n_i is modeled by a square root term because it enables us to describe a decreasing diversity effect (Finn et al., 2013b; Hooper et al., 2005; Schaub, Buchmann, et al., 2020).

In order to account for varying drought risk exposures we conduct stratified random sampling (with replacement). Observations are selected unequally from two sub dataset representing

[15] In the Irish site, the experiment was conducted for three years (2013-2015). In the two Swiss sites experiment were conducted for respectively one year (2011) and two years (2012-2013)

respectively drought conditions (in which a drought experiment was simulated for all observations) and normal conditions (in which no drought experiment was simulated for all observations). Using this sampling method, two scenarios are evaluated: low drought risk exposure (in which we select 20% of observations with a drought treatment and 80% of observations without a drought treatment) and high drought risk exposure (in which we select 40% of observations with a drought treatment and 60% of observations without a drought treatment). This sampling strategies is implemented 1000 times for each drought risk exposure scenario. Then, the econometric analysis is conducted on each sub sample, thus following a bootstrap regression strategy of 1000 iterations for each drought risk exposure scenario. From this first part, we derive the effect of plant diversity on the variance and skewness of yield for two different drought risk exposures.

Economic insurance value. Second, to assess the economic importance of the derived effects we evaluate the insurance value of a certain drought risk exposure for different level of diversity. For this purpose, we consider the following equation describing the decrease in risk premium due to an increase in plant diversity (Di Falco & Chavas, 2009; Schaub, Buchmann, et al., 2020).

$$IV_d(n) = -\frac{\partial RP}{\partial n} = -\frac{1}{2} r_2 {P_m}^2 \frac{\partial Var(y_d)}{\partial n} - \frac{1}{6} r_3 {P_m}^3 \frac{\partial Ske(y_d)}{\partial n} \tag{20}$$

Where IV_d represents the insurance value of an increase of one unit of diversity n (Shannon index) under drought risk exposure d. Moreover, we derive the total insurance value for a certain level of diversity. It follows the following equation:

$$totIV_d(n) = \int_0^n (-\frac{\partial RP}{\partial n})\, dn = \int_0^n (-\frac{1}{2} r_2 {P_m}^2 \frac{\partial Var(y_d)}{\partial n} - \frac{1}{6} r_3 {P_m}^3 \frac{\partial Ske(y_d)}{\partial n})\, dn \tag{21}$$

P_m is the price at which farmers could sell their forage production[16]. $\frac{\partial Var(y_d)}{\partial n}$ represents the effect of an increase in plant diversity on yield variability[17] and $\frac{\partial Ske(y_d)}{\partial n}$ represents the effect of an increase in plant diversity on yield skewness[18]. r_2 is the Arrow-Pratt coefficient of absolute risk aversion. A positive coefficient for r_2 would indicate risk averse farmers. r_3 is the coefficient of downside risk aversion. A negative coefficient for r_3 would indicate downside risk averse farmers. We consider power utility function and a rather risk averse farmers with a coefficient of relative risk aversion $\tau = 2$ (Hardaker et al., 2015). Therefore, r_2 and r_3 can be described by the following equations (Finger, 2013):

$$r_2 = \frac{\tau}{E(\pi)} \tag{22}$$

[16] We assume deterministic prices equal to 23 CHF per 100 kg (Farmers' Union, 2021).
[17] $\frac{\partial Var(y_d)}{\partial n}$ is estimated by $\frac{\beta_{3,d}}{2\sqrt{n}}$ from the econometric model.
[18] $\frac{\partial Ske(y_d)}{\partial n}$ is estimated by $\frac{\beta_{5,d}}{2\sqrt{n}}$ from the econometric model.

$$r_3 = \frac{-(\tau^2 + \tau)}{(E(\pi))^2} \quad (23)$$

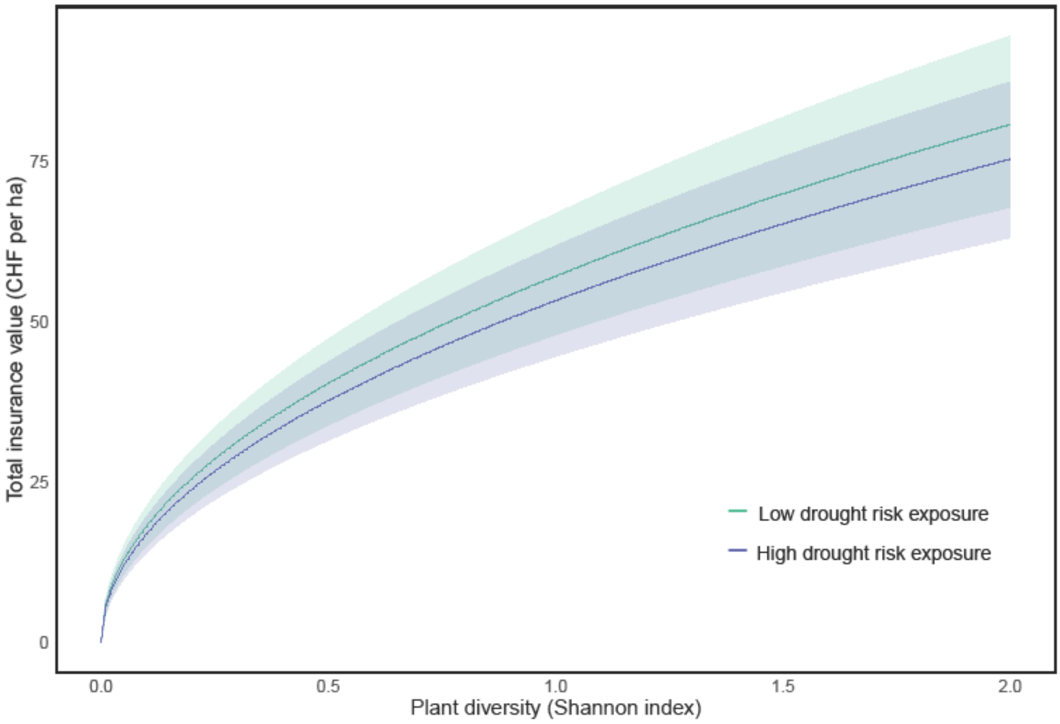
We consider different risk preferences (Chavas, 2004). First, we evaluate the insurance value under constant absolute risk aversion (CARA) where the coefficients of absolute risk aversion r_2 and r_3 are constant across drought risk exposures (we use the mean profit $E(\pi)$ under low drought risk exposure to compute the coefficients). Second, we evaluate the insurance value under constant relative risk aversion (CRRA), which implies decreasing absolute risk aversion (DARA), where the coefficients of absolute risk aversion r_2 and r_3 vary across drought risk exposures (we use different mean profit $E_d(\pi)$ depending on the drought risk exposure to compute the coefficients)
Regarding the second analysis, we conduct the same econometric assessment used for the first analysis (see equations (17) (18) (19)) on the diversity gradient across fields (see figure 1). This allows us to infer the effect of increased plant diversity on yield variance and skewness when plant diversity is implemented across fields. For this purpose, we generate mixed monoculture yield data by randomly sampling and combining monoculture data from the field experiment. We generate data in order to obtain the same diversity levels realized in the experiment (i.e., Shannon index: 0, 0.69, 0.74, 1.34). This allows for a comparison of the effects of diversity on variance and skewness of yield for the two diversity gradients mentioned above.

5. Results

In the following section, we describe the results of the different empirical analyses performed. First, we present the ecological results derived from the stochastic production function analysis of the two diversity gradients (see Figure 1). The results show the effect of plant diversity on yield variance and yield skewness for different drought risk exposures. Secondly, we present the results of the economic assessment of diversity as insurance against drought risk exposure. Here, the value of the insurance (risk premium reduction) of plant diversity is examined under different drought risk exposures.

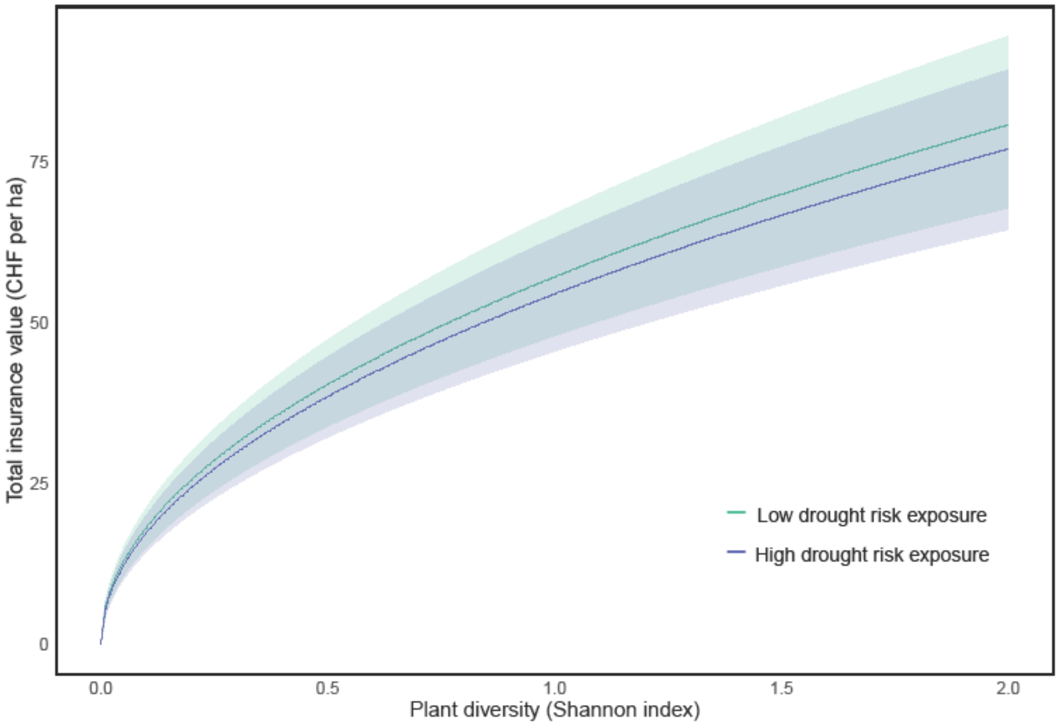
5.1 Insurance value

Figure 2: Total insurance value of plant diversity under CARA



Note: The figure shows the total insurance value for risk averse farmers exhibiting constant absolute risk aversion (r=2) under different drought risk exposure (low=green vs high=purple). The shaded zone represents the interquartile range.

Figure 3: Total insurance value of plant diversity under CRRA

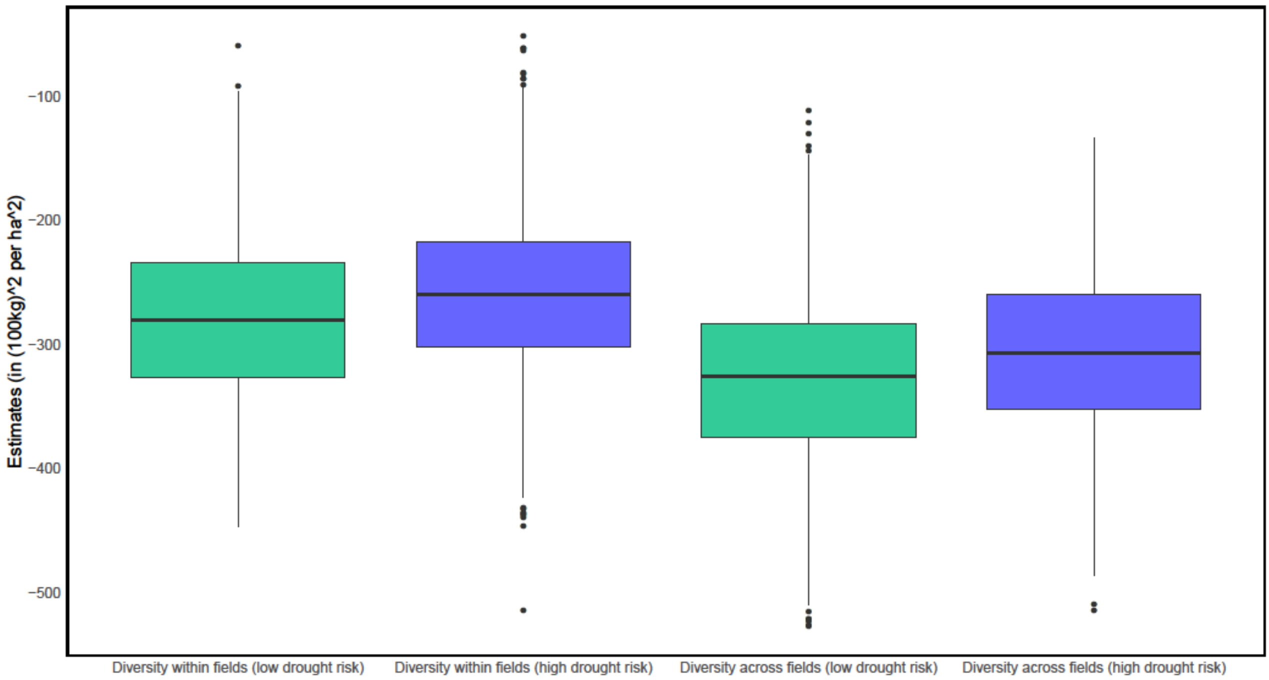


Note: The figure shows the total insurance value for risk averse farmers exhibiting decreasing absolute risk aversion (r=2) under different drought risk exposure (low=green vs high=purple). The shaded zone represents the interquartile range.

Regarding the economic evaluation of plant diversity as a natural insurance against increased drought risk exposure, we find that the farmers' risk premium decreases with increasing plant diversity in both drought risk exposure scenarios. Thus, the insurance value is increasing with plant diversity. Figure 4 shows the total insurance value (cumulative decrease in risk premium in CHF per hectare) under two drought risk exposures (high and low) for farmers exhibiting constant absolute risk aversion. For instance, under low drought risk exposure (blue line), the total insurance value of the most diverse mixture studied (Shannon index = 1.34) is equal to around 66 CHF per hectare. In other words, this means that farmers value the reduction in risk and downside risk derived from plant diversity (Shannon index = 1.34) at 66 CHF per hectare. The level of total insurance value under high drought risk exposure (red line) is lower than under low drought risk exposure. However, the difference is small and not significant, thus it indicates that the total insurance value remains unchanged under high drought risk exposure. Moreover, Figure 5 shows the total insurance value for farmers exhibiting constant relative risk aversion[19]. Through this perspective, the difference between the total insurance value under low and high drought risk exposure is smaller due to the increased absolute risk aversion of farmers under high drought risk exposure.

5.2 Ecological results from stochastic production function

Figure 4: Diversity effect on variance of yield



Note: The figure shows the estimate of the effect of diversity () on yield variance (in $(100kg)^2/ha^2$) for different drought risk exposures (low=green vs high=purple) and for two diversity gradients (diversity within fields on the left and diversity across fields on the right).

The analysis conducted on yield variance shows a negative diminishing effect of plant diversity on yield variance under both drought risk exposure scenarios (high and low) and for both diversity gradient (within fields and across fields). All coefficients are significant at a 1% level. For instance, under low drought risk exposure and while considering diversity

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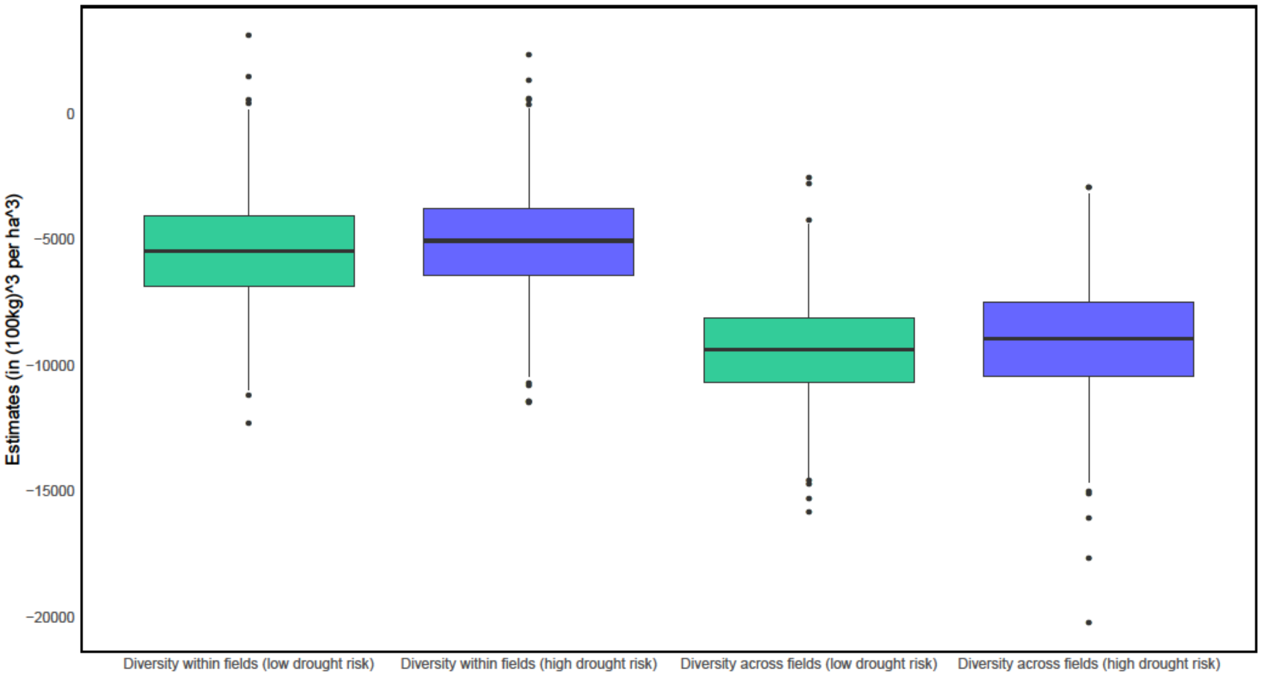
[19] The coefficient of absolute risk aversion is computed by dividing a coefficient of relative risk aversion equal to 2 by respectively the mean yield under low drought risk exposure for the low drought risk exposure coefficient and the mean income under high drought risk exposure scenario for the high drought risk exposure coefficient. Consequently, under high drought risk exposure absolute risk aversion increases due to the lower mean income.

within a field an increase of one root unit of plant diversity (Shannon index) leads to a decrease of yield variance of -279 on average (in $(100kg)^2/ha^2$). The decrease is of around 70% percent in relative terms. This implies that yield variability is reduced by an increase in diversity, thus reducing risk for farmers. These findings support previous research in regards to decreased risk (F. I. Isbell et al., 2009). Regarding the comparison between different drought risk exposure scenarios, the distribution of coefficient (see figure 2) shows that the effect of diversity on yield variance under high drought risk exposure is lower (in absolute terms) than for the low drought risk exposure. However, the difference is not significant, indicating that the effect of plant diversity on yield variance remains unchanged as exposure to drought risk increases. Regarding the comparison between the two diversity gradient (within fields and across fields), we find that that the effect of diversity is higher (in absolute terms) for the diversity gradient across fields but not significantly different. Since multiple monocultures will only be affected by the statistical effect and not by ecological interactions, this indicates that statistical effect due to temporal complementarity between species is the main driver of the risk reducing properties of plant diversity.

Figure 5: Diversity effect on skewness of yield



Note: The figure shows the estimate of the effect of diversity () on yield variance (in $(100kg)^3/ha^3$) for different drought risk exposures (low=green vs high=purple) and for two diversity gradients (diversity within fields on the left and diversity across fields on the right).

Then, the analysis conducted on yield skewness shows a negative diminishing effect of plant diversity on yield skewness under both drought risk exposure scenarios (high and low) and for both diversity gradient (within fields and across fields). All coefficients are significant at a 1% level. For instance, under low 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 -5433 on average (in $(100kg)^3/ha^3$). This implies that yield skewness is reduced by an increase in diversity, thus increasing downside risk for farmers. Regarding the comparison between different drought risk exposure scenarios, the distribution of coefficient (see figure 3) shows that the effect of diversity on yield skewness under high drought risk exposure is higher than for the low drought risk exposure. However, the difference is not significant, indicating that the effect of plant diversity on yield skewness remains unchanged as exposure to drought risk increases. Regarding the comparison between the two diversity gradient (within fields and across fields), we find that that the effect of diversity is lower for the diversity gradient across fields but not significantly different.

6. Conclusion

In this study, we investigate both theoretically and through empirical analysis, the role of plant diversity in acting as a form of natural insurance against the risk of drought in grasslands farming systems. By utilizing a portfolio perspective to examine the diversity of plants, our theoretical framework highlights two distinct ways in which diversity can provide insurance against increased drought risk. These include the ecological interactions between species and the statistical effect resulting from the complementary nature of species over time. Our empirical analysis draws on yield data from grassland experiments to evaluate the impact of plant diversity on farmers' risk premiums under varying levels of drought risk exposure. Our results indicate that plant diversity leads to a decrease in yield variance (risk reduction), but at the same time contribute to more negative skewness (i.e., increasing the downside risk).

Accounting for both effects jointly for a risk averse decision maker, we find that the net effect on farmers' risk premium is negative, demonstrating that plant diversity does offer insurance value. Furthermore, our analysis reveals that this effect remains consistent even under higher levels of drought risk exposure. This supports the share of literature finding similar effect of diversity under drought conditions (Grange et al., 2021). Through a comparison of two diversity gradient analyses, we determine that the statistical effect explored in our theoretical framework is the primary contributor to the insurance value, as opposed to the ecological effect.

Our study does have certain limitations that are worth noting. Firstly, in our empirical analysis we treat plant diversity as an index, thus ignoring the different contributions of specific types of diversity. In reality, functional diversity, as opposed to just any type of diversity, is crucial in ensuring risk-reducing effects from plant diversity (Binder et al., 2018; Kirwan et al., 2007). For instance, combining legume species with grass species can provide additional benefits due to the nitrogen-fixing ability of legumes (Lüscher et al., 2022). However, our analysis does not take these specificities into account. Nevertheless, given the design of the experiment, our diversity gradient (two legumes and two grasses) is closely linked to functional diversity. Therefore, the impact of this limitation may not be significant. Secondly, our analysis is an ex-ante study that seeks to simulate yield variance and skewness by analyzing experimental data, which restricts the generalizability of our results. Utilizing exploratory data could improve the external validity of our analysis. However, to our knowledge, such data is not readily available, and this could serve as an exciting direction for future research.

Biodiversity as a natural insurance holds great interest since it provides both private benefits to farmers through a reduction in their risk premium and public benefits by enhancing the provision of other ecosystem services such as carbon sequestration (Isbell et al., 2011). Understanding the role that biodiversity can play in buffering yield losses in riskier drought environments is therefore essential for establishing sustainable food production systems (Tilman et al., 1996). The overall conclusions of our analysis hold valuable implications for policymakers. Encouraging the use of plant diversity as a form of natural insurance in grasslands can create win-win scenarios by reducing farmers' production risk under extreme weather events such as drought, while also enhancing the provision and stability of ecosystem services. Implementing direct payments to increase the diversity of productive grasslands could be one possible policy option. An additional policy focus shall be on the interrelation of formal insurance systems and their subsidization and the use of natural insurance studied here. Depending on how they interact (i.e., substitutes or complements), subsidizing formal insurance may disincentivize the use of natural insurance, leading to adverse effect on public welfare. Weather index insurance methods, on the other hand, may be a more viable alternative with less potential for adverse effects on other natural insurance strategies (Bucheli et al., 2021). Therefore, policymakers should carefully consider the impact of subsidies on natural insurance strategies, as it could indirectly affect public welfare.

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