Title: Species diversity-income relationship under increasing drought risk

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Abstract: Droughts adversely affect grassland production. Climate change is predicted to cause increasing drought risk and thus to have negative effects on farmers' income and increases income risk. We investigate grassland species diversity as risk management instrument to mitigate adverse drought effects on hay yield. In our paper we, first, provide a theoretical model to investigate effects of increasing drought risk and risk aversion on optimal species diversity choices. We extent earlier work by accounting for different farm types, i.e. whether farmers are net sellers or buyers of hay, as well as market responses to droughts via the hay price. Second, we empirically estimate drought and species diversity effects on hay yield and its variability as well as drought effects on the hay price and its variability. Third, we integrate theoretical and empirical components to simulate implications of species diversity choices. Our theoretical analysis reveals that increasing drought risk negatively affects farmers' certainty equivalent and that species diversity can mitigate these effects. Thus, under increasing drought risk farmers' optimal species diversity level increases. The magnitude of these effects increase with farmers' risk aversion and depend on farm type, i.e. risk exposure. Furthermore, our first empirical results show a substantial positive drought effects on hay price and positive effects on hay price variability, thus price risk. We conclude that species diversity should be taken into consideration in the sustainable management of increasing drought risk, that the extent to use species diversity depends on farmers' risk aversion and farm type and that droughts strongly affect the hay price.

Keywords: Drought, weather risk, species diversity, biodiversity, hay price, yield, sustainable intensification

1. **Introduction**

Weather variability and extreme events are relevant risks for agricultural production (Porter and Semenov 2005, Schlenker and Roberts 2009). Droughts are especially critical for agricultural production and an increase in frequency and magnitude of drought events are expected due to climate change (Dai 2011, Dai 2013, IPCC 2013, Webber et al. 2018, Grillakis 2019), leading to 'increasing drought risk'. This strongly affects grasslands, which are an important forage source for animal production (Huyghe et al. 2014, Barnes et al. 2003, Finger et al. 2013, Ma et al. 2017). In Europe, the 2018 summer drought considerably reduced hay yield, increased the hay price and even caused farmers to slaughter or sell livestock earlier (European Parliament 2018, Schweizer Bauer 2018, Lütke Holz 2019).

We focus here on the role of species diversity in grasslands to reduce farmers risk exposure against increasing drought risk. Species diversity is hypothesized to reduce adverse effects of perturbations, such as droughts, on yield and its stability (Yachi and Loreau 1999). Thus, farmers can use species diversity choices as strategic risk management instrument. Previous research showed that species diversity can reduce hay yield variability (see e.g. Hooper et al. 2005, Isbell et al. 2009, Finger and Buchmann 2015), even when accounting for quality (Schaub et al. n.d.). Additionally, studies that explicitly addressed droughts in grasslands showed, even if results are ambiguous, that species diversity can reduce adverse drought effects on hay yield (Van Ruijven and Berendse 2010, Vogel et al. 2012, Isbell et al. 2015, Hofer et al. 2016, Finn et al. 2018, Haughey et al. 2018).

Economic assessments have focused so far in the assessment of the species diversity effects on the field-level (Schläpfer et al. 2002, Koellner and Schmitz 2006, Finger and Buchmann 2015, Binder et al. 2018). Yet, the integration in a farm-level context as well as the consideration of market-level responses in terms of the hay price have not been considered.

We add to the existing literature in several directions. First, we provide a theoretical model to investigate effects of increasing drought risk exposure, risk aversion and different farm types on optimal species diversity choices. Second, we empirically specify drought and species diversity effects on hay yield and its variability as well as drought effects on hay price and its variability. Third, we integrate the theoretical and empirical components to simulate implications of species diversity choices under different climatic conditions and levels of risk aversion.

A particular focus of our paper is on the possible implications of species diversity for farm management for different farm types. More specifically, we distinguish if farmers are net sellers or buyers of hay. The interaction of increasing drought risk, species diversity and farm type we investigate by using two farm types, hay farmers (net sellers) and milk farmers (net buyers). We assume that farmers include income and income risk considerations in their farm management and that they manage their farm in order to maximize their expected utility, thus, their certainty equivalent. The certainty equivalent is a non-stochastic payment that farmers value equally to a stochastic payment. In our analysis, we focus on the effects of droughts and species diversity on hay yield and hay price and their impacts on farmers' certainty equivalent.

The reminder of this article is organized as follows: First, we develop a theoretical economic model considering interaction of increasing drought risk, hay yield, hay price and species diversity. Second, we perform a theoretical analysis of the processes described in our model. Third, we develop an econometric framework. This is followed by a description of the hay price and weather data as well as the empirical results. Further, we conduct a simulation using our empirical findings. Finally, we discuss and conclude on our findings. Note that our paper presents preliminary results and the empirical applications are not finalized.

2. Economic Model

We present here a stylized economic model for investigating species diversity as a risk management instrument in grasslands to mitigate adverse effects from increasing drought risk. To this end, we focus on the species diversity effect and drought effect on hay yield and its price.

Our model comprises farmers that are net seller or net buyer of hay. For illustration purposes, we focus on two distinct types of farms: either farms that manage grasslands to sell hay (*hay farmers* = net sellers) and/or to feed their ruminants with it to produce milk (*milk farmers* = net buyers). The farmers generate revenue, R_j, by selling their produce, y_j, (hay and/or milk), for milk farmers minus the own hay demand[1], d_{hay}, at its market price, p_j: $R_j = (y_j - d_j)\, p_j$. The index j comprises hay and milk. Additionally, hay and milk production cause costs, C_j. Costs, e.g. for seeds and fertilizer, are deterministic. The income of the two farm types is defined as:

$$\pi_j = R_j - C_j \qquad (1)$$

$E(y_j)$, $E(p_j)$, $E(R_j)$ and $E(\pi_j)$ are the respective expected values. Note that we assume that the conversion of fodder into milk, the demand for hay as well as milk prices to be deterministic.

The income variance are given for hay and milk farmers respectively by[2]:

$$Var(\pi_{hay}) = Var(y_{hay}\, p_{hay}) \qquad (2)$$

$$Var(\pi_{milk}) = Var(y_{milk}\, p_{milk} + y_{hay}\, p_{hay} - d_{hay}\, p_{hay}) = Var(y_{milk}\, p_{milk}) + Var(y_{hay}\, p_{hay}) + Var(d_{hay}\, p_{hay}) + Cov(y_{hay}\, p_{hay}, d_{hay}\, p_{hay}) \qquad (3)$$

Note that $Cov(y_{hay}\, p_{hay}, d_{hay}\, p_{hay})$ is positive and likely to be high.

2.1 Drought, Species Diversity and Hay Production, Price and Costs

Stochastic environmental shocks such as weather or pest infestation contribute to the observed variability of hay yield. Droughts are defined as a situation when plant available water is below a critical threshold over a specific period. Water availability depends on precipitation and evapotranspiration (Vicente-Serrano et al. 2010). In our analysis, we focus on effects of increasing probabilities of drought events, i.e. increasing drought risk, defined as k henceforward. The drought risk is defined by the probability that an index for water

[1] We assume that farmers only balance their hay deficits by buying hay. Balancing deficits only with hay, reflects for example the situation of direct payment systems like in Switzerland where subsidies are linked to maximum use of concentrate of total feed (Mack and Huber 2017). Furthermore, this could be linked to the compliance with label requirements (see e.g. Paredes et al. 2018 for ´haymilk label´).

[2] We assume that hay yield and hay price follow a bivariate normal distribution (see e.g. Burt and Finley 1968; Bohrnstedt and Goldberger 1969). See Appendix 1 for detailed variance definition.

availability, w (see e.g. Tian et al. 2018), falls below a specific threshold (see e.g. Trenberth et al. 2014, Yu et al. 2014, Isbell et al. 2015), see Fig. 1.

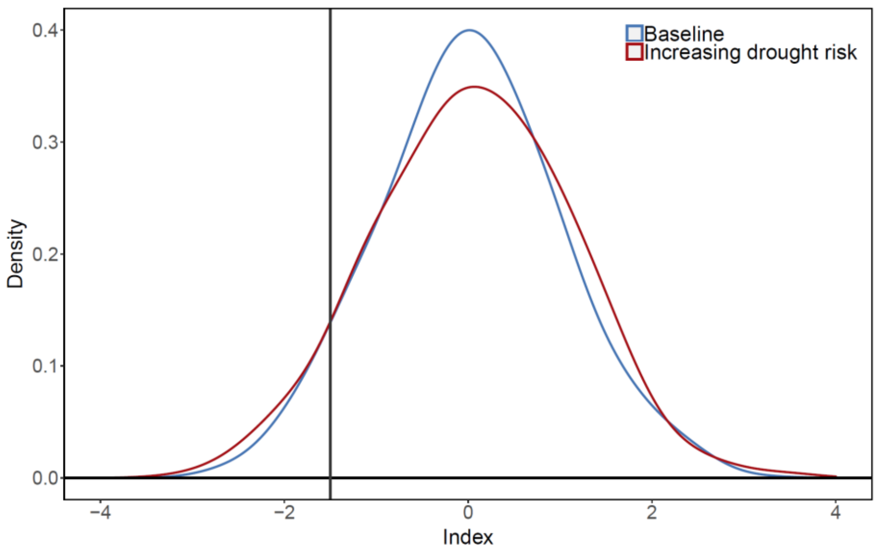

Figure 1. Drought definition and increasing drought risk. Scenario 1 is based on a mean of 0 and a variance of 1 assuming a normal distribution. Scenario 2 is based on scenario 1 with a 10% higher variance. The solid vertical line indicates the drought threshold.

We assume that an increasing number of drought events reduces expected hay yield and increases hay yield variance (Barnes et al. 2003, Ma et al. 2017)[3], i.e.:

$$\frac{\partial E\left(y_{hay}(k)\right)}{\partial k} < 0 \quad (4)$$

$$\frac{\partial Var\left(y_{hay}(k)\right)}{\partial k} > 0 \quad (5)$$

Farmers have a set of management instruments to influence hay production such as various inputs (e.g. irrigation, nitrogen) as well as the level of species diversity, v. Higher species diversity can be achieved by farmers for instance, with sowing or oversowing with mixtures as well as by adjusting fertilization and cutting regimes (see e.g. Walker et al. 2004). Species diversity influences hay production in general and specifically in the event of droughts. In

[3] Our analysis focuses on the role of species diversity to cope with increasing drought risk. The second part of the paper will focus on the empirical relationships, while the first part focusses on the theoretical framework.

general, species diversity is assumed to increase hay yield and it reduces hay yield variability, while both effects reveal saturation (see e.g. Tilman et al. 1996, Hooper et al. 2005, Isbell et al. 2009, Marquard et al. 2009, Finn et al. 2013, Finger and Buchmann 2015), hence:

$$\frac{\partial E\left(y_{hay}(k,v)\right)}{\partial v} > 0 \;\&\; \frac{\partial^2 E\left(y_{hay}(k,v)\right)}{\partial^2 v} \leq 0 \tag{6}$$

$$\frac{\partial Var\left(y_{hay}(k,v)\right)}{\partial v} < 0 \;\&\; \frac{\partial^2 Var\left(y_{hay}(k,v)\right)}{\partial^2 v} \geq 0 \tag{7}$$

In the event of droughts, species diversity is hypothesized to reduce yield losses and decrease variability, yet with diminishing returns (Yachi and Loreau 1999). We therefore assume:

$$\frac{\partial^2 E\left(y_{hay}(k,v)\right)}{\partial k \partial v} > 0 \;\&\; \frac{\partial^3 E\left(y_{hay}(k,v)\right)}{\partial k \partial^2 v} \leq 0 \tag{8}$$

$$\frac{\partial Var\left(y_{hay}(k,v)\right)}{\partial k \partial v} < 0 \;\&\; \frac{\partial^3 Var\left(y_{hay}(k,v)\right)}{\partial k \partial^2 v} \geq 0 \tag{9}$$

Droughts are systemic and thus decrease the aggregated hay supply in a region, Y, which is the sum of hay yields of individual farmers ($Y_{hay} = \sum_{i=1}^{n} y_{hay,i}$). Given the negative relationship of aggregated hay supply and the hay market price droughts leads to an increase in the hay price. Further, as droughts increase hay yield variance droughts also increase variance of aggregated hay supply, thus, the variance of hay price. Therefore:

$$\frac{\partial E\left(p_{hay}(k,Y)\right)}{\partial k} > 0 \tag{10}$$

$$\frac{\partial Var\left(p_{hay}(k,Y)\right)}{\partial k} > 0 \tag{11}$$

Within a region the hay yield of a farm and the regional aggregated supply are assumed to be positively but not perfectly correlated (McKinnon 1967). Hence, the hay yield of a farmer is negatively correlated with the hay price, which mechanism is called ‘natural hedge’ and this mechanism mitigates the income risk. The natural hedge is often found to be 'imperfect', i.e. $-1 < cor(y_{hay}, p_{hay}) < 0$ (see e.g. Finger 2012).

We assume that farmers are price takers and their decisions do not affect the regional aggregated hay supply. We thus also neglect possible effects of species diversity choices on hay price.

Costs of hay production in our models are a function of species diversity, with the properties:

$$\frac{\partial c_{hay}(v)}{\partial v} > 0 \ \& \ \frac{\partial^2 c_{hay}(v)}{\partial^2 v} \geq 0 \tag{12}$$

Costs are non-random as farmers decide on the species diversity level in the beginning of the year. By deciding on a specific species diversity level farmers select a specific 'lottery' (Crocker and Shogren 2001, Baumgärtner 2007), i.e. a lottery with a specific mean and variance of income.

2.2 Farmers Optimal Species Diversity Decisions

Farmers are concerned about the level of income they generate and, if not risk neutral, about the income risk. We assume risk averse farmers that maximize their Von Neumann-Morgenstern expected utility function. Thus, we consider farmers' utility function, $U(\cdot)$, to be monotonic ($U' > 0$) and to reflect risk aversion ($U'' < 0$).

In the expected utility framework the cost of risk bearing by an individual can be determined by the risk premium, RP (see e.g. Chavas 2004). The risk premium represents the amount that leaves a farmer indifferent between stochastic income from hay production and a certain, non-stochastic payment equal to the certainty equivalent (CE):

$$CE_j = \mathrm{E}(\pi_j) - RP_j \tag{13}$$

The risk premium can approximate as follows (Pratt 1964):

$$RP_j \approx \frac{1}{2}\, r\, Var(\pi_j) \tag{14}$$

Where r is the Arrow-Pratt risk coefficient of risk aversion, with the properties $r = -U''/U'$ and, for a risk-averse decision maker, $r > 0$.

Farmers chose optimal species diversity level, v^*, that is certainty equivalent maximizing, i.e. $\max_{v} CE_j(k, v)$, resulting in the following optimality condition (Baumgärtner 2007):

$$\frac{\partial E\left(\pi_j(v^*)\right) - \left(RP_j(v^*)\right)}{\partial v} = \frac{\partial\left(C_j(v^*)\right)}{\partial v} \tag{15}$$

Farmers chose species diversity at a level where the marginal certainty equivalent is equal to marginal cost of species diversity provision. The optimal level of species diversity, v^*, increases with farmers' degree of risk aversion, r, i.e. $\frac{\partial v^*}{\partial r} > 0$ (see also Baumgärtner 2007).

3. Theoretical Analysis

In the theoretical analysis, we focus on implication for the optimal species diversity level and for the certainty equivalent when examining the following three aspects: i) impact of increasing drought risk (3.1), ii) species diversity to manage increasing droughts risk (3.2) and iii) different implications for hay and milk farmers considering the previous two aspects (3.3).

3.1 Increasing Drought Risk:

Lemma 1. *Increasing drought risk decreases farmer's certainty equivalent:*

$$\frac{\partial CE_j}{\partial k} < 0 \tag{16}$$

(*Proof 1, Appendix 1*)

Droughts decrease the expected hay yield while increasing its variance, i.e. production risk, and droughts increase the expected hay price while increasing its variance, i.e. price risk, as we outlined above. Given that the natural hedge is imperfect, droughts reduce farmers expected income and increase its variance, i.e. income risk. Consequently, an increasing drought risk decreases the certainty equivalent. This holds for hay and milk farmers.

3.2 Species Diversity to Manage Increasing Drought Risk

Proposition 1. *Increasing drought risk increases the marginal certainty equivalent of species diversity and thus farmers' optimal level of species diversity, v^*:*

$$\frac{\partial^2 CE_j}{\partial k\, \partial v} > 0 \tag{17}$$

&

$$\frac{\partial v^*}{\partial k} > 0 \tag{18}$$

(*Proof 2, Appendix 1*).

We outlined above that species diversity can mitigate negative impacts from droughts, as species diversity increases the expected hay yield and decreases its production risk[4]. Hence, we can show that farmers will respond to higher drought risk with higher levels of species diversity. The response will depend on the level of risk aversion of farmers.

3.3 Different Implications for Hay and Milk Farmers

The adverse income effect of increasing drought risk differ between farm types, as milk farmers compared to hay farmers do not benefit from the natural hedge as they produce hay to meet their own hay demand and do not to sell it. Which means, when the hay yield is low and falls short their own hay demand milk farmers need to buy hay at a high price. Consequently, the farm types differ in their strategy to manage increasing drought risk with respect to species diversity:

[4] Note that we assume that species diversity does not influence the hay price as only a small share of farmers use species diversity for farm management. If we would assume that many farmers use species diversity for farm management, i.e. the regional species diversity level is affected, therefore trough the regional aggregated supply the hay price our findings still hold, however, the effect sizes of species diversity would be smaller in most cases.

Proposition 2. *Increasing drought risk has stronger implications for milk farmers than for hay farmers, i.e. increases in the marginal certainty equivalent of species diversity and the optimal species diversity levels, v^*, are higher for milk farmers:*

$$\frac{\partial^2 CE_{milk}}{\partial k\, \partial v} > \frac{\partial^2 CE_{hay}}{\partial k\, \partial v} > 0 \tag{19}$$

$$\frac{\partial v^*_{milk}}{\partial k} > \frac{\partial v^*_{hay}}{\partial k} > 0 \tag{20}$$

(*Proof 3, Appendix 1*).

Under increasing drought risk the marginal effect of species diversity on expected income does not differ between hay and milk farmers as long as species diversity does not lead to a price response. However, as the marginal species diversity effect on income variance is more decreasing for milk than for hay farmers, the marginal species diversity effect on the certainty equivalent is greater and the optimal species diversity level is higher for milk than for hay farmers, considering that farmers are risk adverse.

4. Econometric framework

Based on the theoretical background presented above, we now proceed with three steps. First, we empirically assess drought effects on hay prices and hay price variability. Second, we quantify effects of droughts and species diversity on hay yield and hay yield variability. Third, we combine all components to simulate implications of species diversity choices under different climatic conditions and farmers' levels of risk aversion. In this section, we present the econometric framework to investigate the former points.

4.1 Hay Price

To analyse the effect of droughts on the hay price we use a structural vector autoregressive model of type A (SVAR; see e.g. Lütkepohl 2005).[5] A SVAR model can be used to investigate exogenous shock (e.g. droughts) on other endogenous variable (e.g. price). Our SVAR has the following form:

[5] For analysing the price data we used the R-packages ´vars´ and ´urca´ (Pfaff 2008, Pfaff et al. 2016).

$$AX_t = \mu_t + A_1^* X_{t-1} + \cdots + A_j^* X_{t-j} + B\varepsilon_t \tag{21}$$

The index t indicates the time and d the number of lags in the model. X_t is the vector of K variables, i.e. drought and the hay price. μ_t comprises a constant and monthly dummies. A_j^* for $j = 1, \dots, d$ are the coefficient matrices ($K \times K$). B is in an A-type SVAR model an identity matrix, I_K, and ε_t is the structural error, which is assumed to be white noise. For identification of our structural model, we impose the restriction on A that droughts affect the hay price but the hay price not droughts:

$$A = \begin{bmatrix} 1 & 0 \\ \alpha_{21} & 1 \end{bmatrix} \tag{22}$$

4.2 Hay Yield

For identifying the effects of droughts, species diversity and the interaction of those on hay yield and its variance we will use a Just and Pope stochastic production function framework (Just and Pope 1978). First, we can estimate these effects on hay yield by using a stochastic production function, specified as:

$$y_{hay,i} = \beta_0 + \beta_\gamma \gamma_i + \beta_v v_i + \beta_{v\gamma} \gamma_i v_i + \beta_X Z_i + e_{1,i} \tag{23}$$

where $y_{hay,i}$ is hay yield of plot i, β_0 is an intercept, γ_i[6] indicates a drought, v_i is the species diversity level, $\gamma_i v_i$ represents the interaction of drought and species diversity and Z_i is a set of control variables. The error term, $e_{1,i}$ includes all uncontrolled factors and is assumed to have an expected value of zero. Second, the estimation of hay yield variance, which is defined for the estimation as $Var(y_{hay,i}) = (y_{hay,i} - \bar{y}_{hay,i})^2 = e_{1,i}^2$, is specified as:

$$Var(y_{hay,i}) = \beta_0 + \beta_\gamma \gamma_i + \beta_v v_i + \beta_{v\gamma} \gamma_i v_i + \beta_X Z_i + e_{2,i} \tag{24}$$

We use robust standard errors to correct for heteroscedasticity, which is assumed by the species diversity, i.e. hay yield variance changes with species diversity.

[6] Note that γ indicates a drought event while k indicates increasing drought risk.

4.3 Simulation

In the simulation we will simulate the results for our theoretical model using empirical estimates for average farms for both farm types. For simulating the effects on different climatic conditions we vary the probabilities of drought events and we vary farmers´ risk aversion.

5. Data

5.1 Hay Price Data

The hay price is the monthly reported average wholesale price ex-farm including value added tax for high-pressure pressed hay in South Germany in Euro $100kg^{-1}$ and are provided by the Bavarian Association of Farmers (Fig. 2). The hay price data covers the period from August 2002 to March 2019. The hay price data is rather unique and of high quality as hay price data are seldom reported over such long time spans and with such a frequency. We transformed the hay price into the real hay price using the harmonized index of consumer prices for Germany with base year 2015 taken from Eurostat (Eurostat 2019) and we took the natural logarithm of this real hay price. This transformed hay price are henceforth referred to as hay price.

5.2 Hay Yield Data

Hay yield data will be taken from biodiversity experiments that include experimental droughts. Hence, this data comprises experimental species diversity and hay yield information of treated (drought) and not treated (control) plots. Biodiversity experiment data, without experimental droughts, is usually used by economic studies of species diversity (Schläpfer et al. 2002, Koellner and Schmitz 2006, Finger and Buchmann 2015, Binder et al. 2018, Schaub et al. n.d.).

5.3 Weather Data

We use a standardized drought index, the Standardized Precipitation Evapotranspiration Index (SPEI), for identifying droughts. SPEI incorporates information about precipitation and potential evapotranspiration (Vicente-Serrano et al. 2010). In detail, we used a SPEI that comprises information about the last three months (3-month SPEI) and we considered only the main vegetation period (from April to October). Further, we defined droughts when the SPEI ≤ -1.5, which cutoff represents 'severe droughts' (Yu et al. 2014). In the following, we use as our drought variable the absolute value of SPEI when it indicates a severe drought otherwise the variable is zero.

To identify droughts in South Germany, for analyzing the drought effect on the hay price, we used monthly potential evapotranspiration and precipitation data from January 1991 to March 2019 provided by German Meteorological Office as 1km x 1km gridded data (DWD 2019). Further, we computed from potential evapotranspiration and precipitation the 3-month-SPEI[7] for every 1km x 1km grid of South Germany and calculated the average for South Germany from it. In a next step we computed the drought variable for each month (Fig. 2).

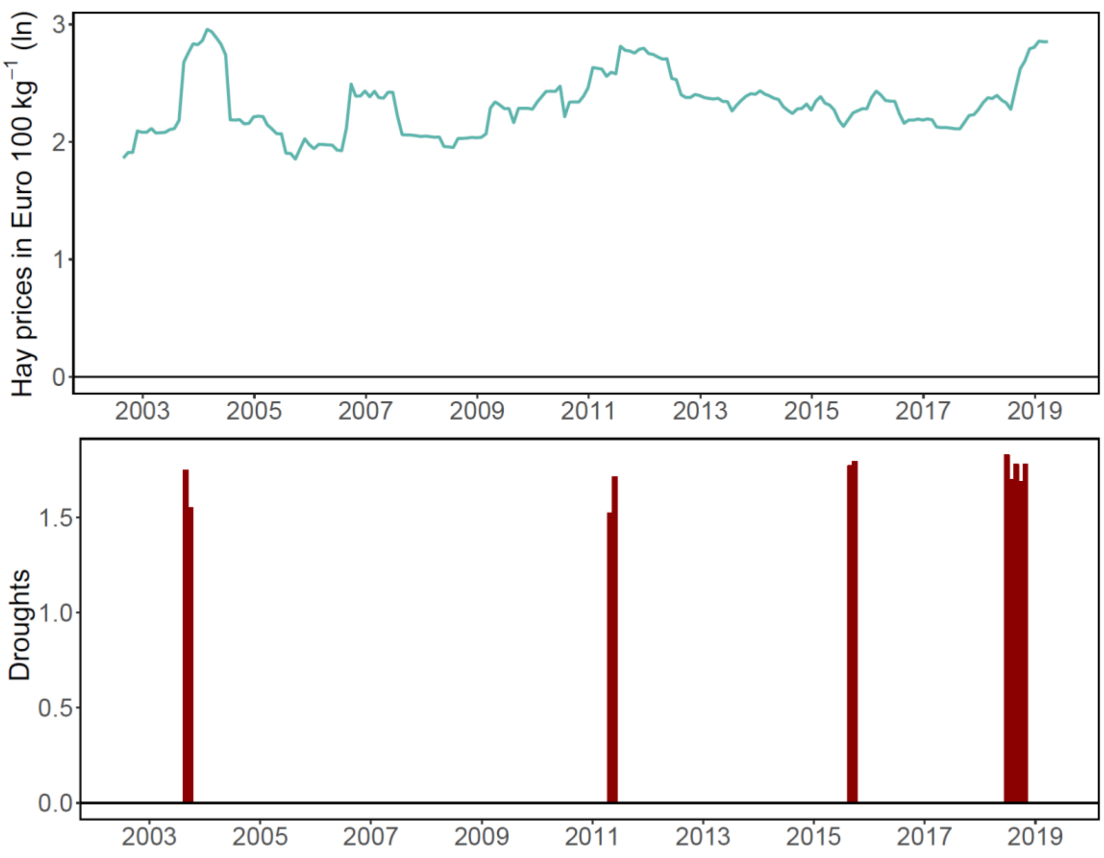

Figure 2: Hay price and droughts from August 2002 to March 2019 in South Germany.

[7] For calculating the SPEI we used the R-packages ´SPEI´ (Beguería and Vicente-Serrano 2013).

The hay price and the drought time series of Southern Germany are both stationary, the suggested lag length (d) by information criterions is 3 and droughts affect the hay price (see Appendix 2 for details).

6. First Empirical Results

6.1 Hay Price:

We used the impulse response function (IRF) and forecast error variance decomposition (FEVD) to illustrate the drought effects on the hay price and its variance (see e.g. Lütkepohl 2005 for details). The IRF shows that the hay price strongly increases after a drought event, by up to +19.5% in month 6, and that the positive drought effect remains significant over 16 months (Fig. 3). We also found no compensation for the high price in the following periods as the effect decays over time to zero. Considering a yearly perspective, i.e. a perspective when the lost yields due to droughts are compensated by the next year yields, the average effect on the hay price is 14%. The FEVD shows that a drought event causes in the short-term perspective of 1 month only 0.1% of the hay price variance, but, over time this amounts to 4.6% in 12 month and 5.1% for months ≥20 (Table 2).

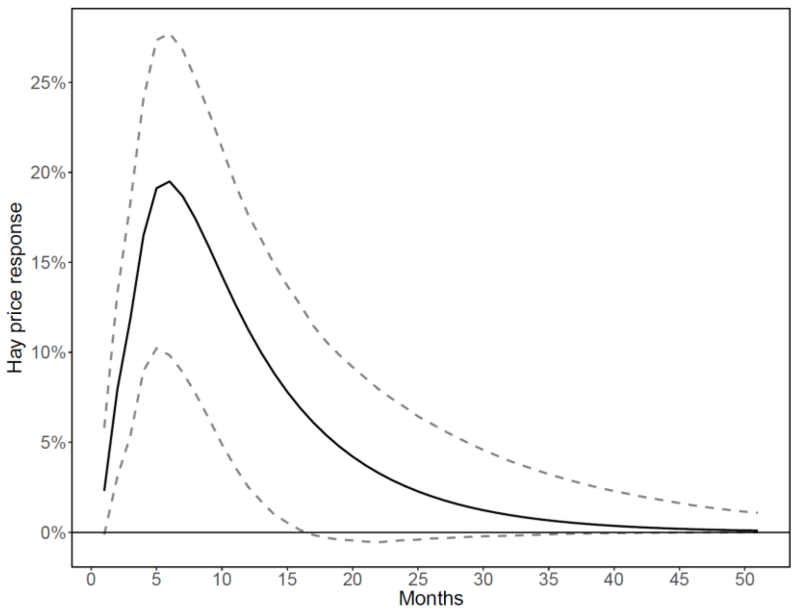

Figure 3: Impulse response function of the hay price in percent to a drought event. The dashed gray line indicates the 95%-confidence interval. We used for the SVAR estimation the BFGS algorithm.

Table 2: Hay price variance decomposition

Month	Drought	Hay price
1	0.1%	99.9%
4	1.3%	98.7%
8	3.6%	96.4%
12	4.6%	95.4%
16	4.9%	95.1%
≥20	5.1%	94.9%

7. Discussion

We analyzed the effect of increasing drought risk on farmers and how species diversity can be used to mitigate adverse effects, in this analysis we explicitly addressed implication for different farm types using theoretical and empirical analysis.

7.1 Theoretical results

We addressed the theoretical analysis three aspects in detail: First, increasing drought risk decreases farmer's certainty equivalent (*Lemma 1*). We outlined that farmers experience losses due to increasing drought risk given a negative effect on hay yield and an imperfect natural hedge. These losses are likewise for risk averse, neutral and loving farmers. Under increasing drought risk, risk averse farmers´ certainty equivalent decreases additionally as production and price risk, thus income risk, increases.

Second, increasing drought risk increases the marginal certainty equivalent of species diversity and thus farmers' optimal level of species diversity (*Proposition 1*). We proofed that this is true for farmers independent of their risk aversion, however, for risk averse farmers the marginal certainty equivalent of species diversity and the optimal species diversity level are even higher. In our model we assumed that the hay price is not reactive to changes of species diversity. If such response would be created, the impact of species diversity would reduce, i.e. we would find less increase in the marginal certainty equivalent of species diversity and optimal species diversity level, however, given the natural hedge the before described effects would remain.

Third, increasing drought risk has stronger implications for milk farmers than for hay farmers (*Proposition 2*). Hay and milk farmers are differently affected by increasing drought risk as hay farmers (or more generally speaking farmers that in drought years have a greater hay yield than hay demand $= y_{hay} > d_{hay}$) benefit from natural hedge whereas milk farmers (or more generally speaking farmers that in drought years have a lower hay yield than hay demand $= y_{hay} < d_{hay}$) need to purchase at hay at a higher hay price. We showed that the use of species diversity can in the following reduce adverse increasing drought risk effects for both farm types. Yet, two aspects in this context are important, first the expected income changes likewise, as we assume no hay price effect when farmers use higher species diversity levels, and second, the marginal effect on risk reduction is greater for milk farmers. Consequently, in a population of risk averse farmers species diversity is more beneficial for milk farmers than for hay farmers, thus, the optimal species diversity level of milk farmers is higher. In contrast, for risk neutral farmers the benefits are the same for both farm types and for risk loving farmers species diversity is more beneficial for hay farmers.

Additionally, we can derive from our results that milk farmers can manage their losses in certainty equivalent from increasing drought risk by adjusting their risk exposure, i.e. relationship between hay yield and hay demand, to benefit from the natural hedge or at least to not have to buy at a high price in the event of a drought ($= if\ drought\ y_{hay} - d_{hay} \geq 0$). In our economic model we assumed that farmers can purchase hay from somewhere, however, when no hay or other appropriate substitutes[8] are available droughts might lead for milk farmers even to emergency slaughtering, which would even lead to higher losses. Milk farmers would deviate from their milk production plan and the meat market would be over-supplied leading most likely to a lower milk price. We focused in the analysis on hay yield and hay price, but if we consider that the milk price would be positively affected by droughts we would most likely find effects with the same signs as outlined above because the regional milk market is supplied by a large region (Fousekis et al. 2017, Zhang 2017) whereas the hay market is supplied by a small region (Rudstrom 2004), thus, is likely that the milk price reduces less in response to droughts than the hay price. Hence, if the milk market incorporates a natural hedge it can be assumed to be lower than one of the hay market.

[8] Note that farmers are often constraint by substitution hay with other feed as they produce under certain schemes (see e.g. Mack and Huber 2017 or Paredes et al. 2018) or simply for other economic and agricultural reasons.

7.2 Insights from first empirical applications

The empirical analysis showed that the hay price increases substantially after a drought event and that the positive effect persists for a bit over one year. The duration of this effect can be caused by the time it takes to compensate for the 'drought' harvest by the next year harvest at this time, plus some time the market needs to adjust to new hay yield availability. Ubilava (2017) found a similar response time for wheat prices. Additionally, we showed that droughts caused price risk, as they increased hay price variability.

Note that the empirical analysis of hay yield data is not finalized, however, other studies showed that hay yield decreased and its variance increased with droughts (Barnes et al. 2003, Ma et al. 2017). Moreover, we are confident given the current empirical literature on droughts in grasslands, even though it is reporting ambiguous results on the measures resistance, resilience, recovery and stability (Pfisterer and Schmid, B. 2002, Van Ruijven and Berendse 2010, Vogel et al. 2012, Isbell et al. 2015, Finn et al. 2018, Haughey et al. 2018), that species diversity under increasing drought risk will have a positive effect on expected yield and/or negative effect on yield variance as most studies reported positive effect on at least one of the measures. This confidence is also supported by findings from Hofer et al. (2016) that showed that plants are either largely resistant or resilient to droughts.

7.3 Next steps

In the further development of our paper, we will include data from biodiversity experiments to investigate the effect of droughts, thus increasing drought risk, on hay yield and the effect of species diversity in this regard. Moreover, for investigating the economic relevance of the effects identified in our theoretical analysis we will employ our empirical results in a simulation. Furthermore, our paper offers interesting extensions: does the social and private optimum differ from each other given market price responses, risk aversion and differences in farm types, do policies and insurances impact these optima and can they be used to align the social and private optimum?

8. Conclusion and Implication

Overall, our results show that species diversity can be a management risk instrument to mitigate adverse effects from increasing drought risk. Here, we showed that farmers with higher risk aversion and farmers with higher risk exposure benefit more from species diversity as well as that droughts substantially affect the hay price. Hence, species diversity should be taken into consideration in the sustainable management of grasslands.

Our findings have several relevant implications: While increasing drought risk cause decreasing expected hay yield and increasing the expected hay price, the variance of both, yield and price, are expected to increase. Therefore, risk averse farmers will experience greater loses and need to manage these risk more extensively, such as with higher species diversity levels. Moreover, policy makers as well as breeders should address different farm types differently, in this paper we presented these types as distinctive versions of hay and milk farmers, however, our findings also hold for the entire gradient between these distinct farm types. For example for breeders these differences in response to droughts between farm types could mean that they should offer to milk farmers mixtures with higher shares of more drought resistant C4 plants than for hay farmers, while for policy makers compensation payments when a drought occurred could be linked with information about the farm type.

Droughts can alter the species composition in grasslands and lead to reduction in species diversity (see e.g. Fahey et al. 2018), therefore and for the reasons outlined above, it is important to increase and maintain grassland species diversity. Here sowing or oversowing with mixtures and management adaptation can help (see e.g. Walker et al. 2004). Current developments in precision farming, as targeted overseeding, might offer sustainable and more cost efficiently practice to increase and maintain species diversity (Finger et al. 2019). In general, cost reduction in the provision of more species diverse grasslands would also increases in the optimal species diversity level.

Finally, we want to highlight that, independently from species diversity, our analysis showed that it is important to consider differences in farm types, in terms of whether the agricultural production is sold directly after the first production stage or further processed within the farm, even when the farms produce the same product.

9. Appendix 1

9.1 Detailed variance definition

The hay and milk farmers' income variances are defined in detail as follows, considering that i) hay yield and hay price follow a bivariate normal distribution (see e.g. Burt and Finley 1968, Bohrnstedt and Goldberger 1969) and ii) we assume deterministic milk production and milk price levels, which are uncorrelated with hay production and which are not influenced by droughts:

$$Var(\pi_{hay}) = E(y_{hay})^2\, Var(p_{hay}) + E(p_{hay})^2\, Var(y_{hay}) + 2\, E(y_{hay})\, E(p_{hay})\, Cov(y_{hay}, p_{hay}) + Var(p_{hay})\, Var(y_{hay}) + Cov(y_{hay}, p_{hay})^2 \quad \text{(A.1)}$$

$$\begin{aligned} Var(\pi_{milk}) &= E(y_{milk}\, p_{milk})^2 + E(y_{hay})^2\, Var(p_{hay}) + E(p_{hay})^2\, Var(y_{hay}) + \\ &2\, E(y_{hay})\, E(p_{hay})\, Cov(y_{hay}, p_{hay}) + Var(p_{hay})\, Var(y_{hay}) + Cov(y_{hay}, p_{hay})^2 + \\ &d_{hay}^2\, Var(p_{hay}) + E(p_{hay})^2\, Var(d_{hay}) + 2\, d_{hay}\, E(p_{hay})\, Cov(d_{hay}, p_{hay}) + \\ &Var(p_{hay})\, Var(d_{hay}) + Cov(d_{hay}, p_{hay})^2 + Cov(y_{hay}\, p_{hay}, d_{hay}\, p_{hay}) \\ &= E(y_{milk}\, p_{milk})^2 + E(y_{hay})^2\, Var(p_{hay}) + E(p_{hay})^2\, Var(y_{hay}) + \\ &2\, E(y_{hay})\, E(p_{hay})\, Cov(y_{hay}, p_{hay}) + Var(p_{hay})\, Var(y_{hay}) + Cov(y_{hay}, p_{hay})^2 + \\ &d_{hay}^2\, Var(p_{hay}) + Cov(y_{hay}\, p_{hay}, d_{hay}\, p_{hay}) \end{aligned} \quad \text{(A.2)}$$

9.2 Proof 1. *– Lemma 1. Increasing drought risk decreases farmer's certainty equivalent:*

First, the drought effect on expected income (equation 1) is negative, i.e. $\frac{\partial E(\pi_j)}{\partial k} < 0$, considering that costs, hay demand, milk production and price are not affected by droughts as well as an 'imperfect' natural hedge. Second, droughts cause income variance to increase (equation A.1 and A.2), as the variance of hay yield and hay price increase, which are not perfectly negative correlated, i.e. $\frac{\partial Var(\pi_j)}{\partial k} > 0$. Therefore, increasing drought risk decreases farmer's certainty equivalent:

$$\frac{\partial CE_j}{\partial k} < 0 \quad \text{(A.3)}$$

9.3 Proof 2. – *Proposition 1. Increasing drought risk increases the marginal certainty equivalent of species diversity and thus increases farmers' optimal level of species diversity, $\boldsymbol{v}^*$:*

The marginal effect of species diversity on expected revenues increases with drought risk $\frac{\partial^2 E(\pi_j)}{\partial k\, \partial v} = \frac{\partial^2 E(y_{hay})}{\partial k\, \partial v} > 0$. This condition holds under the condition that there are no feedback effects on hay price levels, i.e. $\frac{\partial E^2(p_{hay})}{\partial k\, \partial v} = 0$. Moreover, the marginal effect of species diversity on variance reduction increases with drought risk $\frac{\partial^2 Var(\pi_j)}{\partial k\, \partial v} = \frac{\partial^2 Var(y_{hay})}{\partial k\, \partial v} < 0$. Thus, the marginal certainty equivalent of species diversity increases with increasing drought risk:

$$\frac{\partial^2 CE_j}{\partial k\, \partial v} > 0 \qquad \text{(A.4)}$$

We can proof that increasing drought risk increases farmers' optimal species diversity level by using the implicit function theorem:

$$\frac{\partial v^*}{\partial k} = -\ \frac{\partial^2 CE}{\partial v\, \partial k} \Big/ \frac{\partial^2 CE}{\partial^2 v} \qquad \text{(A.5)}$$

Moreover, from equation 6, 7 and 12 we can derive:

$$\frac{\partial^2 CE}{\partial^2 v} < 0 \qquad \text{(A.6)}$$

Consequently, we can show that A.5 is positive and that increasing drought risk increases farmers' optimal level of species diversity:

$$\frac{\partial v^*}{\partial k} > 0 \qquad \text{(A.7)}$$

9.4 Proof 3. – *Proposition 2. Increasing drought risk has stronger implications for milk farmers than for hay farmers, i.e. increases in the marginal certainty equivalent of species diversity and the optimal species diversity levels, $\boldsymbol{v}^*$, are higher for milk farmers:*

First, the impact of increasing drought risk on the income of hay and milk farmers can be expressed as:

$$\frac{\partial E(\pi_{hay})}{\partial k} = \frac{\partial E(y_{hay})}{\partial k} E(p_{hay}) + \frac{\partial E(p_{hay})}{\partial k} E(y_{hay}) + \frac{\partial Cov(E(y_{hay}),E(p_{hay}))}{\partial k} \quad \text{(A.8)}$$

$$\frac{\partial E(\pi_{milk})}{\partial k} = \frac{\partial E(y_{hay}) - \partial d_{hay}}{\partial k} E(p_{hay}) + \frac{\partial E(p_{hay})}{\partial k} \left(E(y_{hay}) - d_{hay}\right) + \frac{\partial Cov\left(E(y_{hay}) - d_{hay}, E(p_{hay})\right)}{\partial k} \quad \text{(A.9)}$$

Considering that the increasing drought risk impact on covariance of equations A.8 and A.9, describes the joint variability under increasing drought risk of either $E(y_{hay})$ and $E(p_{hay})$ or $\left(E(y_{hay}\right) - d_{hay}$ and $E(p_{hay})$, we can express the derivatives for hay and milk farmers as $\frac{\partial E(y_{hay})}{\partial k}\frac{\partial E(p_{hay})}{\partial k}$ and $\frac{\partial E(y_{hay}) - d_{hay}}{\partial k}\frac{\partial E(p_{hay})}{\partial k}$, respectively. These two expressions correspond to the natural hedge effect on income.

Accordingly to A.8 and A.9, the marginal effect of species diversity on expected income with increasing drought risk are given by $\frac{\partial^2 E(y_{hay})}{\partial k \partial v} E(p_{hay})$. This holds under the condition that there are no feedback effects on hay price levels, i.e. $\frac{\partial E^2(p_{hay})}{\partial k\, \partial v} = 0$, and on hay demand, i.e. $\frac{\partial d_{hay}}{\partial k\, \partial v} = 0$.[9]

Second, the impact of increasing drought risk on income variance of hay and milk farmers is:

[9] Note that with price feedback (i.e. if many farmers adapt higher levels of species diversity), milk farmers would gain in terms of expected income additionally compared to hay farmers:

$$\frac{\partial^2 E(\pi_{hay})}{\partial k\, \partial v} = \frac{\partial^2 E(y_{hay})}{\partial k\, \partial v} E(p_{hay}) + \frac{\partial^2 E(p_{hay})}{\partial k\, \partial v} E(y_{hay}) + \frac{\partial^2 E(y_{hay})}{\partial k\, \partial v}\frac{\partial E(p_{hay})}{\partial k\, \partial v}$$

$$\frac{\partial^2 E(\pi_{milk})}{\partial k\, \partial v} = \frac{\partial^2 E(y_{hay}) - \partial d_{hay}}{\partial k\, \partial v} E(p_{hay}) + \frac{\partial^2 E(p_{hay})}{\partial k\, \partial v}\left(E(y_{hay}) - d_{hay}\right) + \frac{\partial^2 E(y_{hay}) - \partial d_{hay}}{\partial k\, \partial v}\frac{\partial^2 E(p_{hay})}{\partial k\, \partial v}$$

Where $\frac{\partial E(p_{hay})}{\partial k\, \partial v} E(y_{hay}) < 0$ and $\frac{\partial^2 E(p_{hay})}{\partial k\, \partial v}\left(E(y_{hay}) - d_{hay}\right) \geq 0$ when $E(y_{hay}) \leq d_{hay}$. Moreover, $\frac{\partial E(p_{hay})}{\partial k\, \partial v} E(y_{hay}) < \frac{\partial^2 E(p_{hay})}{\partial k\, \partial v}\left(E(y_{hay}) - d_{hay}\right)$ also when $E(y_{hay}) \leq d_{hay}$ as long as $d_{hay} > 0$.

$$\frac{\partial Var(\pi_{hay})}{\partial k} =$$

$$\frac{\partial E(y_{hay})^2\, Var(p_{hay}) + E(p_{hay})^2\, Var(y_{hay}) + 2\, E(y_{hay})\, E(p_{hay})\, Cov(y_{hay}, p_{hay}) + Var(p_{hay})\, Var(y_{hay}) + Cov(y_{hay}, p_{hay})^2}{\partial k}$$

(A.10)

$$\frac{\partial Var(\pi_{milk})}{\partial k} =$$

$$\frac{\partial E(y_{hay})^2\, Var(p_{hay}) + E(p_{hay})^2\, Var(y_{hay}) + 2\, E(y_{hay})\, E(p_{hay})\, Cov(y_{hay}, p_{hay}) + Var(p_{hay})\, Var(y_{hay}) + Cov(y_{hay}, p_{hay})^2}{\partial k} +$$

$$\frac{\partial d_{hay}^2\, Var(p_{hay})}{\partial k} + \frac{\partial Cov(y_{hay}\, p_{hay}, d_{hay}\, p_{hay})}{\partial k} \quad \text{(A.11)}$$

Hence, the marginal effect of species diversity on income variance, considering absence of hay price feedbacks, can be expressed for our farm types respectively as:

$$\frac{\partial^2 Var(\pi_{hay})}{\partial k \partial v} =$$

$$\frac{\partial^2 E(y_{hay})^2\, Var(p_{hay}) + E(p_{hay})^2\, Var(y_{hay}) + 2\, E(y_{hay})\, E(p_{hay})\, Cov(y_{hay}, p_{hay}) + Var(p_{hay})\, Var(y_{hay}) + Cov(y_{hay}, p_{hay})^2}{\partial k \partial v}$$

(A.12)

$$\frac{\partial^2 Var(\pi_{milk})}{\partial k \partial v} =$$

$$\frac{\partial^2 E(y_{hay})^2\, Var(p_{hay}) + E(p_{hay})^2\, Var(y_{hay}) + 2\, E(y_{hay})\, E(p_{hay})\, Cov(y_{hay}, p_{hay}) + Var(p_{hay})\, Var(y_{hay}) + Cov(y_{hay}, p_{hay})^2}{\partial k} +$$

$$\frac{\partial^2 Cov(y_{hay}\, p_{hay}, d_{hay}\, p_{hay})}{\partial k \partial v} \quad \text{(A.13)}$$

The marginal effect of species diversity on variance differ between the two farm types by $\frac{\partial^2 Cov(y_{hay}\, p_{hay}, d_{hay}\, p_{hay})}{\partial k \partial v}$, which is negative.[10] Thus, the marginal certainty equivalent of species diversity increases with increasing drought risk more for milk farmers than for hay farmers:

$$\frac{\partial^2 CE_{milk}}{\partial k\, \partial v} > \frac{\partial^2 CE_{hay}}{\partial k\, \partial v} > 0 \quad \text{(A.14)}$$

[10] Note that with price feedback milk farmers would gain in terms of expected income variance additionally compared to hay farmers:
$\frac{\partial^2 d_{hay}^2\, Var(p_{hay})}{\partial k\, \partial v} < 0$ when $d_{hay} > 0$.

We can therefore proof that increasing drought risk increases milk farmers' optimal species diversity level more than hay farmers' optimal species diversity level by following A.5 to A.7:

$$\frac{\partial v_{milk}^{*}}{\partial k} > \frac{\partial v_{hay}^{*}}{\partial k} > 0 \qquad \text{(A.15)}$$

10. Appendix 2

10.1 Stationarity, Lag Length and Granger Causality

We used an Augmented Dicky Fueller (ADF) test with a drift (see Pfaff et al. 2016) to test for stationarity of the hay price time series and without a drift to test for stationarity of the drought time series. We found both time series to be stationary (Table A1). Further, the information criterion Akaike information criterion (AIC), Hannan-Quinn criterion (HQ) and Final Prediction Error criterion (FPE) suggest a lag length (d) of 3, whereas the Schwarz criterion (SC) suggests $d = 1$, when including a constant and monthly dummies.[11] Using the Granger causality test, we found that droughts Granger cause the hay price but the hay price do not Granger cause droughts (Table A3), which makes intuitively sense. This supports the use of a SVAR model, in which droughts affect the hay price.

Table A1: Augmented Dicky Fuller test

Test statistic	tau3	phi2 (drift)
Hay price	-2.92**	4.38*
Droughts	-5.55***	-

*, **, *** denote significance at the 10%, 5% and 1% level, respectively. Critical values can be find in Table A2.

Table A2: Critical values for the Augmented Dickey Fuller test

	With drift		Without drift
	tau3	phi2 (drift)	tau3
1pct	-3.46	6.52	-2.58
5pct	-2.88	4.63	-1.95
10pct	-2.57	3.81	-1.62

[11] Without controlling for the months all information criterion suggest $d = 2$.

Table A3: Granger causality test

Null hypothesis	F-Statistic	p-value
Droughts ↛ Hay price	7.00	0.0002
Hay price ↛ Droughts	0.77	0.51

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