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The role of weather derivatives and portfolio effects in agricultural water management

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Abstract

Restrictive irrigation water policies established due to e.g. environmental concerns or water scarcity appear to result in declining farm income and arising risk exposure in terms of yield uncertainty. With this in mind, we investigate the potential of index-based weather insurance, which is also known as weather derivatives, to cope with the economic disadvantages for farmers resulting from a reduction in water quotas and increased water prices. By means of a whole-farm risk programming approach, we systematically compare crop portfolios without and with the possibility of purchasing standardized weather derivatives based on precipitation and temperature indices. In doing so, we allow for crop diversification as well as water reallocation between crops. Thus, overcoming some of the shortcomings inherent to previous studies in this strand of research. In an application to a representative cash crop farm in northern Germany, we found that the use of weather derivatives offsets the loss in the farmer's certainty equivalent resulting from moderate reductions in water quotas and water price increases. Our results also indicate that weather derivatives have the potential to substantially alter farm plans and the optimal irrigation water demand. Far reaching environmental implications might be the consequence which require further attention and careful consideration by policymakers.

Keywords: Irrigation, index-based weather insurance, whole-farm risk programming

1. Introduction

Globally, irrigation has substantially contributed to reduce negative economic consequences associated with the absence of precipitation indicating that risk aversion among farmers is one reason for shifting from rainfed agriculture to irrigation (Perry et al. 2009). Moreover, irrigation has considerably promoted economic growth and has increased the productivity of the agricultural sector as well as to satisfy the world's food demand, while water availability is declining worldwide (World Bank 2006). This comes with rising competition for water resources within and across the agricultural and domestic sector (Giordano and Villholth 2007). Similarly, growing population pressures, improved living standards, and the increasing awareness of environmental concerns have placed the need for an enhanced water resources management on the policy agenda (Johansson et al. 2002).

In regards to indicating essential water savings, a vast amount of literature reveals that a stricter regulation of irrigation water – e.g. by means of water pricing schemes or water quotas – results in diminishing farm income (cf., e.g. Dono et al. 2010; Giannoccaro et al. 2010;

Lenouvel and Montginoul 2010; Viaggi et al. 2010). Moreover, crop yield variability appears to increase involving further risks for farmers (Finger 2012; Garrido et al. 2006). In order to mitigate the economic disadvantages caused by restrictive water and irrigation policies, farmers may reallocate the available irrigation water between crops, adjust the crop-specific irrigation intensity or alter crop portfolios to better balance risks (Buchholz and Musshoff 2013).

In addition to on-farm risk management instruments, such as irrigation, a variety of market-based agricultural insurance products that aim to hedge weather related risks are offered to farmers in nowadays. More recently, a new class of index-based weather insurance, also known as weather derivatives, has been a promising field of research for coping with weather risks in agricultural production. Unlike traditional crop insurance, weather derivatives are used to hedge risk caused by weather events, such as heat or drought, instead of the loss inherent to these weather events (Turvey 2001). To do so, an index is designed that is based on an underlying weather index, such as growing degree days, which is measured objectively at a specific weather station for a certain period of time. Thus, the payoff of the derivative is independent of the farm-specific yield shortfall occurring in the case of unfavorable weather conditions. This procedure avoids moral hazard and minimizes adverse selection problems that commonly apply to traditional crop yield insurance (Vedenov and Barnett 2004). However, there is the disadvantage that the payoff of the weather derivative does not perfectly correspond to the actual shortfall in the underlying exposure (Woodard and Garcia 2008). This is generally referred to as basis risk which mainly comprises a geographical basis risk related to different weather conditions at the reference weather station and the production site as well as to a local basis risk entailing the fact that the weather variable which determines the payoff of the derivative is not the only parameter relevant to explain a shortfall in crop yields.

Although agricultural insurance in general and weather derivatives in particular as well as irrigated agriculture are used to mitigate the consequences of weather-related risks, surprisingly little effort has been made to investigate these different types of risk management instruments in a joint analysis. The existing studies fall into three distinct categories: analysis of discrete farm plans (A), optimizing approaches with one single production activity in an expected utility maximizing framework (B) and econometric analyses (C).

(A) Barham et al. (2011) compare discrete combinations of multiple-peril crop insurance and varying levels of irrigation in a stochastic simulation setting for a cotton farm in Texas. Their findings show that the crop insurance is particularly beneficial at lower irrigation levels.

(B) Dalton et al. (2004) contrast the benefits of multiple-peril crop insurance and the investment in supplemental irrigation for potato production in Maine. Lin et al. (2008) investigate irrigation strategies for maize production in Georgia in case of varying water prices and the availability of a precipitation-based weather derivative. Their results reveal that the derivative performs relatively poorly in terms of increasing the estimated certainty equivalent revenues and has no impact on the amount of irrigation water used.

(C) Mafoua and Turvey (2003) provide a conceptual regression model using annual cross sectional data from New Jersey. They demonstrate that precipitation-based weather derivatives may enable farmers to hedge against irrigation costs in drought years. Foudi and Erdlenbruch (2012) reveal in a more recent study with French Farmers based on a probit model that the adoption to irrigation is lower when farmers purchase yield insurance. Thus, the offered yield insurance, as they further conclude, may serve to decrease the amount of water used for irrigation.

Although, the studies mentioned above consider possible interdependencies between the risk management instruments ‘irrigation’ and the analyzed ‘insurance products’, possible adjustments with regard to the choice of crop portfolios are not directly taken into account. Bearing in mind that farmers usually grow a multitude of crops which respond differently to unfavorable weather conditions or restricted irrigation capabilities, an integrated approach is necessary if various strategies for hedging weather risks are available (Berg and Schmitz 2008). This holds especially true when the use of irrigation water resources induced by changing water and irrigation policies is restricted. The present study addresses these limitations and suggests the additional consideration of weather derivatives to the field of agricultural water management in general, and policymakers as well as farmers in particular. More specifically, the two following research questions are the purpose of this investigation:

1) How does the provision of weather derivatives affect risk-efficient portfolio crop choice and, thus, the irrigation water demand at the farm level?
2) Can index-based weather derivatives be used to mitigate the economic disadvantages as well as the arising risk exposure for farmers resulting from a reduction in water quotas or increased water prices?

In doing so, this paper is – to the best of our knowledge – the first that contributes a whole-farm risk programming approach that allows for the adjustment of the crop portfolio, the purchase of weather derivatives and water reallocation between crops combined in an integrated framework. Moreover, our investigation relies on a unique panel of crop-specific micro data. That is, yield uncertainty is incorporated into our model based on irrigation field trials, rather than on expert opinions or crop modeling techniques predominantly used in this research strand. The analysis is applied to a representative cash crop farm situated in the northeastern part of the German Region of Lower Saxony that is highly dependent on irrigation using withdrawn groundwater.

The remainder of the paper is structured as follows: In section 2, we explain the risk programming approach as well as the design and pricing of the weather derivatives. Subsequently, section 3 reveals a description of the database including the case study farm as well as the applied bootstrap simulations. The investigated water policy scenarios and the respective whole-farm model results are presented in section 4 and, finally, the paper ends with conclusions (section 5).

2. Methodological procedure

2.1 The risk programming approach for jointly analyzing irrigation and weather derivatives

In order to analyze irrigation and weather derivatives as complementary risk management instruments in a whole-farm context, we apply a quadratic risk programming approach that is based on an expected value - variance framework (EV). Here, we focus on the expected total gross margin of the farm plan $E(y)$ which is subject to the expected single gross margins $E(GM^j)$ per unit of the production activity j and the water price WP per unit of applied irrigation water IR^j. Furthermore, x^j denotes the underlying activity levels.

$$E(y) = \sum_{j=1}^{J} \left(E(GM^j) - WP \cdot IR^j \right) \cdot x^j \tag{1}$$

Aside from the crop-based production activities, the farmer has the ability to sign different types of weather derivatives which are incorporated as additional activities into the EV model. Supposing a linear combination of the single activities and normally distributed single gross margins, the variance of the expected total gross margin $VAR(y)$ can be calculated by using the weighted activity levels x^j, standard deviations σ^j and σ^k as well as the correlation coefficients $\rho^{j,k}$ (cf., e.g. Markowitz 1952, p. 81):

$$VAR(y) = \sum_{j=1}^{J} (x^j \cdot \sigma^j)^2 + 2 \cdot \sum_{j=1}^{J} \sum_{k<j}^{J} x^j \cdot \sigma^j \cdot x^k \cdot \sigma^k \cdot \rho^{j,k} \tag{2}$$

Subsequently, assuming a decision maker with a negative exponential utility function and constant absolute risk aversion, the certainty equivalent CE can be defined as the expected value $E(y)$ less a risk premium which equals one-half of the variance of the expected total gross margin multiplied with the coefficient of constant absolute risk aversion λ (cf., e.g. Robinson and Barry 1987). More specifically, the optimization problem considered here is formulated to maximize the decision maker's certainty equivalent for a given set of farm-specific constraints and varying irrigation water policy scenarios:

Maximize

$$CE = E(y) - \frac{1}{2} \cdot \lambda \cdot VAR(y) \tag{3}$$

subject to:

$$\sum_{j=1}^{J} IR^j \cdot x^j \leq \overline{TIW} \tag{4}$$

$$\sum_{j=1}^{J} a^{ij} \cdot x^j \leq b^i, \text{with } i = 1, 2, \ldots, I \tag{5}$$

$$x^j \geq 0 \tag{6}$$

Equation (4) constrains the total amount of irrigation water allowed $\overline{TIW}$. By varying the water price WP and the total amount of irrigation water allowed $\overline{TIW}$, we investigate differentiated water policy scenarios. In the latter case, the water price is set to zero. Although it is generally possible, we do not analyze the introduction of water prices for a restricted amount of irrigation water; that is, a combination of both water policies. Equation (5) defines the resource restrictions, where b^i denotes the amount of the resource i available and a^{ij} denotes the resource requirements per unit of production activity j. In this regard, we account for the total amount of arable land available, the labor capacity, crop rotation requirements as well as production quotas or related constraints. According to equation (6), the production activity j is confined to positive values.

The farmer's risk attitude is implemented by the coefficient of constant absolute risk aversion

λ. However, the elicitation of individual risk attitudes, or risk aversion coefficients, for the use in economic analysis in general and applications in whole-farm risk programming in particular, still remains a major challenge (Hudson et al. 2005; Lybbert et al. 2013). To address this problem, risk aversion coefficients are commonly parameterized or taken as standard figures. According to Musshoff et al. (2008), however, the variance of the expected total gross margin associated with the farm plan that was realized empirically by the farmer can be used to reveal his/her subjective risk acceptance. To make use of this information, the above-described EV model can be formulated as an income maximizing[1] program in which the empirically observed variance of the expected total gross margin serves as risk constraint. By solving the alternative program in a first step, that is, maximizing the expected total gross margin, also the shadow price of the risk constraint is obtained which multiplied with the factor 2 equals the Arrow-Pratt measure of constant absolute risk-aversion (cf., e.g. Turvey 2012). In doing so, we recover the farmer's coefficient of absolute risk aversion from the empirically observed variance of the expected total gross margin which is, subsequently, included in equation (3).

In contrast to parameterizing risk aversion coefficients or using risk constraints, this procedure is advantageous for two reasons: First, the risk attitude of the farmer is explicitly incorporated into the model. This is necessary as we analyze the farmer's demand for the risk management instrument 'weather derivatives' and therefore require an explicit knowledge of the risk attitude. Second, from a methodological perspective, the use of a fixed risk constraint in an EV context may involve decreasing (increasing) risk aversion for a fall (rise) in farm income when constant absolute risk aversion applies. As changing water policy regulations tend to have an impact on the magnitude of farm income, a fixed risk constraint may not only influence portfolio selection, but also the willingness to pay for weather derivatives.

2.2 Design and pricing of weather derivatives

Although being highly exposed to weather related risk, thus far, farmers in general, and specifically in Germany have rarely used weather derivatives (cf., e.g. Kellner and Musshoff 2011; Smith and Glauber 2012). To show the potential of these insurance products, we design standardized index-based weather derivatives which are hypothetically offered to the farmer over-the-counter (OTC). Crop water demand is not only dependent on the amount of

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[1] Alternatively, minimizing the portfolio variance for a given level of income would provide an identical risk-efficient frontier since the risk-minimizing solution is the dual of the risk constrained maximizing program (Turvey et al. 2005). In this case, however, the risk aversion coefficient is recovered from two times the inverse of the shadow price of the income constraint.

precipitation, but also on temperature as one driver of evaporation. We therefore consider both, a precipitation-based and a temperature-based weather derivative corresponding to drought and heat, respectively, in order to implicitly mimic these biological plant-climate relationships. As farmers can select various production activities, the weather derivatives are not initially fitted to a specific crop. The accumulation period lasts from the beginning of May until the end of July since the majority of the available crops appear to respond most considerably to lacking irrigation applications in Lower Saxony during this time period. To account for insufficient precipitation or drought events, we specify a so-called dry day (DD) index that forms the basis of the precipitation-based derivative:

$$DD^a = \sum_{t=01.05.}^{31.07.} \begin{cases} 1, if\ R^{a,t} \leq 0 \\ 0, if\ R^{a,t} \geq 0 \end{cases}, with\ a = 1, \dots, N \tag{7}$$

Where $R^{a,t}$ is the average precipitation in millimeter (mm) at day t in year a, and the DD-defining threshold is set to 0 mm. Thus, the DD index responds to the count of days without precipitation within the period May 1 until July 31. By using an analogy with financial call options, the payoff P_{DD}^a of the corresponding DD weather derivative is specified as follows:

$$P_{DD}^a = max(DD^a - S_{DD}, 0) \cdot V_{DD} \tag{8}$$

Where DD^a is the index value, S_{DD} denotes the strike level, and the difference thereof is multiplied with the tick size V_{DD} being set to € 1/DD. Consequently, the DD weather derivative generates a payoff for the farmer if the count of days without any precipitation exceeds the previously agreed strike level S_{DD}.

For temperature, we chose a growing degree days (GDD) index which commonly intends to determine the impact of temperature on crop development during the growing season and can also be used for specifying weather derivatives (cf., e.g. Xu et al. 2010):

$$GDD^a = \sum_{t=01.05.}^{31.07.} max\left(T^{a,t} - \hat{T}, 0\right), with\ a = 1, \dots, N \tag{9}$$

Here, $T^{a,t}$ denotes the average temperature in degree Celsius (°C) at day t in year a, while $\hat{T}$ refers to the minimum temperature required for crop stimulation. Although being crop-specific, $\hat{T}$ is set to a constant value of 5 °C. The corresponding payoff of the GDD weather derivative P_{GDD}^a is formulated analogously to the above-mentioned case:

$$P_{GDD}^a = max(GDD^a - S_{GDD}, 0) \cdot V_{GDD} \tag{10}$$

Accordingly, the farmer receives a payoff in year a if the underlying index GDD^a which, in other words, includes the truncated, accumulated temperatures occurring within the period May 1 until July 31, exceeds the strike level S_{GDD}. Here, the tick size V_{GDD} is defined as € 1/°C. For the DD as well as the GDD weather derivatives, the strike level corresponds to the N-year average index value.

The actuarial fair premium is estimated by means of the burn rate method (Jewson and Brix 2005). Put simply, the hypothetical payoffs or the indemnity payment of the weather derivatives that would have been realized over a N-year period are calculated in order to price[2] the weather derivatives. Thus, the fair premium generates an expected gross margin $E\left(GM^{j}\right)$ of zero for the farmer (Musshoff et al. 2008). However, the fair premium neglects the underwriter's profit margin and transaction costs that inevitably incur when derivatives are offered on a commercial basis. Therefore, we add a load of 20 % of the fair premium on the price of the weather derivatives. From the farmer's perspective, the loading results in a negative expected gross margin of the weather derivatives in the amount of the loading representing the true costs of these insurance products.

Weather derivatives can only contribute effectively to mitigate the arising risk exposure from restricted irrigation capabilities when the payoff of the underlying weather index is negatively correlated with the crop-based production activities' single gross margins. To assess the risk-reducing potential of the considered weather derivatives at the farm level, we systematically compare crop portfolios without and with the possibility of purchasing weather derivatives. Hence, the risk-reducing potential is quantified as percentage change in the standard deviation of the expected total gross margin.

3. Data

3.1 Case study farm

The aforementioned approach is applied to a representative cash crop farm situated in the northeastern part of Lower Saxony which is also known as Germany's major irrigation area. Historically, in this region located south to Hamburg, farmers have mainly used groundwater resources for irrigation and are therefore able to grow a multitude of water-demanding crops ranging from ware potatoes, sugar beets to winter wheat, for instance. Thus, despite poor soil quality, a highly specialized cash crop farming system could be established which is however heavily dependent on irrigation since annual precipitation rarely satisfies the crop water demand. In particular, ware potato cropping requires additional irrigation on these sites in

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[2] The disount rate is assumed to be 0 %.

order to ensure a sufficient product quality that complies with the standards of the processing and retailing industries. Moreover, the cultivation of silage maize for biogas production has also gained in importance in recent years and might involve further water demand.

By assumption, hose-reel irrigation machines, pumps and related technical facilities are already installed, so that, technically, the entirety of arable land can be irrigated. Therefore, overhead costs of the irrigation systems are not relevant for the farmer's decision-making process. The farmer can grow winter wheat, winter barley, ware potatoes, sugar beets, and silage maize for biogas production. In addition, it is possible to set areas aside. The arable land amounts to 180 ha representing approximately the average size of those farms that comprise more than 100 ha and manage about 70 % of the total arable land in the region under investigation (LSKN 2012).

3.2 Single gross margins and weather data

Crop yields and the corresponding irrigation water applications are based on irrigation field trials carried out in the considered region between 2006 and 2012 (LWK several years). The trial site was established in 2006 and is characterized by silty sand and an average annual amount of precipitation of 622 mm. For each of the considered crops, three different irrigation intensities, namely rainfed cropping, deficit irrigation starting below 35 % available water capacity (35 % AWC), and intensive irrigation starting below 50 % available water capacity (50 % AWC), can be chosen. Product prices and variable costs for the planning period of 2013 are specified in compliance with the data provided by regional extension services. Variable irrigation costs are estimated to amount to € 1.80/mm. The farmer hedges product prices of the considered crops by means of forward contracts. Thus, we focus solely on the variation of the crop yields observed in the field trials.

Daily average precipitation $R^{a,t}$ and daily average temperature $T^{a,t}$ data was recorded directly at the trial site and is also available. Therefore, geographical basis risk is almost completely excluded from the analysis. Using the crop yield and weather data, we compute time series of the crop-based production activities' single gross margins net of the variable irrigation costs as well as of the payoff of the weather derivatives for the period from 2006 to 2012.

3.3 Crop yield distribution choice and bootstrap sampling estimates

In recent years, a vast amount of research reveals disagreement about how to specify the characteristics of crop yield distributions. Just and Weninger (1999) state that evidence is not yet sufficient to disprove normality and find crop yields to be reasonably characterized by a normal distribution. Similarly, the impact of irrigation on crop yield distributions remains unclear. For instance, Atwood et al. (2003) reject the normality for crop yield residuals of irrigated maize, sorghum, and wheat among other crops in an application to farm-level yield data from Kansas (USA). On the contrary, Harri et al. (2009) particularly confirm that crop yields for maize grown in the irrigated plains of Kansas and Nebraska are normally distributed. More broadly, Hennessy (2009) argues that irrigation might eliminate the left tail of the crop yield distribution which would result in an increasing skewness. This, in turn, is partly contradicted by the findings of a recent study by Du et al. (2012) who demonstrate that irrigation boosts the skewness of maize and soybean, while the opposite applies to wheat.

Considering the aforementioned findings and the rather short single gross margin time series, we do not test for stochastic processes. Instead and in line with the standard approach that is widely used in the literature (Hardaker et al. 2004), we confine the analysis to normally distributed single gross margins of all irrigated crops and the offered weather derivatives. The single gross margin of set-aside areas are however deterministic.

In order to correct for statistical bias, bootstrap simulations are applied (Efron and Tibshirani 1993). This means that we replace the empirical standard deviations and correlation coefficients by their respective bootstrap estimates to be included into the risk programming model. In doing so, we randomly draw 10,000 bootstrap samples with replacement from the original data. Thereby, we keep the structure between the single gross margins of the considered production activities to account for possible interdependency. Table 1 depicts the expected gross margins as well as the corresponding standard deviations of the production activities. In addition, the coefficients of variation and the average amount of irrigation water applied in the field trials are revealed.

[Please insert Table 1 about here.]

It becomes apparent that additional irrigation tends to increase the expected gross margins. However, differences in the expected total gross margin between deficit and intensive irrigation appear to be relatively small. In case of winter wheat and silage maize, reduced irrigation is even superior in contrast to intensive irrigation. Except for barley, reduced irrigation leads to diminishing standard deviations for all crops considered. However, only for ware potatoes and sugar beets intensive irrigation contributes to a further decrease in the standard deviation. Moreover, irrigation involves decreasing coefficients of variation in general. This also illustrates the risk-reducing effect in terms of the change in the relative variation of the expected gross margins resulting from the use of irrigation. Due to the loading on the fair premium, the expected gross margins of the weather derivatives are negative. The DD and GDD derivatives differ in the magnitude of their expected total gross margins. Nevertheless, both weather derivatives exhibit the same relative level of the loading on the fair premium.

Table 2 reports the correlation coefficients between the single gross margins of the activities. Considering the crop-based production activities, there are strong positive correlations between both irrigated alternatives of each crop. This also applies to the winter cereal gross margins since winter wheat and winter barley have similar growing seasons as well as resource requirements.

[Please insert Table 2 about here.]

In contrast, the silage maize gross margins are negatively correlated with the winter cereals gross margins. Furthermore, the ware potato gross margins tend to be negatively correlated with the winter barley gross margins. Moreover, the majority of the single gross margins of the crop-based production activities exhibit pronounced negative correlations with the payoffs of the DD as well as of the GDD weather derivative meaning that both derivatives appear to be effective risk management instruments. These differences to perfect negative correlations reflect the local basis risk.

3.4 Baseline scenario and irrigation water policy settings

Currently, local water supply agencies grant an uncharged irrigation water quota of 144,000 m³ corresponding to 80 mm per year and hectare to the farmer. Under these circumstances and in the absence of weather derivatives, the crop rotation of the 180 ha arable land farmed comprises 25 % of ware potatoes with intensive irrigation as well as 27 % of winter barley, 20 % of silage maize, 15 % of winter wheat and 13 % of sugar beets with deficit irrigation. The expected total gross margin of the empirically chosen farm plan amounts to € 288,968 or € 1,605/ha, respectively. Thereby, the farmer implicitly accepts a standard deviation of the expected total gross margin of € 64,874 or € 360/ha being his/her subjective risk acceptance. The recovered coefficient of absolute risk aversion amounts to 0.000021 which is commonly assumed to reflect a slightly pronounced risk aversion (Raskin and Cochran 1986).

The potential benefits for the farmer resulting from the possibility of purchasing weather derivatives are examined for the following irrigation and water policy settings: Besides the currently granted 80 mm in the base scenario, water quotas of 60, 40 and 20 mm as well as a total ban on irrigation are analyzed. We proceed similarly in order to assess the implications of increased irrigation water prices: Beginning with € 0/mm additional costs for water withdrawals, water prices of € 0.5/mm, € 1/mm, € 1.5/mm and € 2/mm are chosen. In this regard, we assume an unlimited availability of irrigation water. Thus, the actual amount used is solely dependent on the farmer's water demand and is not restricted by the water quota currently enforced.

4. Results

4.1 Irrigation water demand and portfolio crop choice

In response to changing water policies the farmer may alter the crop portfolio, reallocate irrigation water and sign weather derivative contracts. Our first objective is to analyze how the provision of weather derivatives affects the farmer's crop and irrigation choice. In this regard, Table 3 and Table 4 summarize the model results for a reduction in water quotas and increased water prices, respectively. For each water policy scenario, results are shown without and with the possibility of purchasing weather derivatives. At a first glance, the use of weather derivatives has no effect on the total amount of irrigation water used by the farmer in case of reduced water quotas (Table 3). This is mainly due to the fact that the granted water quotas appear to be rather restrictive and are fully used in all cases. In contrast, a comparison of the farmer's irrigation water demand for increased water prices without and with weather derivatives reveals ambiguous findings (Table 4). While the irrigation water demand remains unchanged in case of an unlimited water availability (€ 0/mm) as well as for a water price of € 1/mm, the amount of irrigation water declines from 100 mm to 91 mm for a water price increase to € 0.5/mm if weather derivatives are available. On the contrary, the opposite applies for a further rise in water prices with a boost in the water demand from 48 mm to 78 mm at a water price of € 2/mm, for instance. Thus, our results indicate that the farmer's water demand does not generally decrease if the weather derivatives are available. In this regard, a rise (fall) in the water demand tends to be contingent on the trade-off between the marginal cost related to additional insurance and the diversification of the crop acreage including the irrigation reallocation, respectively, for which the optimization is simultaneously solved (Turvey 1992).

[Please insert Table 3 and Table 4 about here.]

Moreover, Table 3 and Table 4 portray the corresponding farm plans. Generally, it appears that irrigation of winter wheat and winter barley is reduced first when the available irrigation water is further restricted. Similarly, irrigation is only applied to silage maize for low water prices. On the contrary, sugar beets and ware potatoes tend to use the applied irrigation water rather efficiently with ware potatoes being irrigated intensively (50 % AWC) in all water pricing scenarios. Furthermore, the provision of weather derivatives to the farmer involves substantial adjustments in the crop portfolios. Although these changes are specific to the analyzed water policy scenarios, less irrigation tends to be applied to sugar beets, whereas water applications for winter barley partly increase if weather derivatives are available. In other words, we find a partial reduction in the amount of applied irrigation which, however, appears to be offset by a reallocation of the formerly used water resources towards production activities which would be irrigated at a lower intensity or which would not be irrigated if weather derivatives were unavailable. In this regard, Seo et al. (2005) report comparable effects and demonstrate that participation in yield and revenue insurance programs may result in an increasing nitrogen fertilizer usage. More specifically, they distinguish between an ‘intensive margin’ referring to a reduced input intensity and the ‘extensive margin’ which is due to the expansion of nitrogen demanding crops. In line with the results presented above, they conclude that the ‘extensive margin’ dominates the ‘intensive margin’ effect which would increase the optimal input rate.

In addition to the crop allocation patterns, Table 3 and Table 4 also include the amount of signed weather derivatives. Generally, the farmer exhibits a strongly pronounced demand for both the precipitation-based DD derivative and the temperature-based GDD derivative in all water policy scenarios. While the amount of weather derivatives tends to moderately increase as the available water quota is further reduced, there is no clear tendency for the range of increased water prices. The extent to which either the amount of the DD or of the GDD derivative changes in the optimum solutions depends on the shift in the farm plan as well as on how the single production activities are correlated with the weather derivatives. As a result, evaluating the insurance effect of weather derivatives in consideration of portfolio effects is rather complex (Berg and Schmitz 2008). In all scenarios, the number of signed DD derivative contracts clearly exceeds the count of GDD weather derivatives. Multiplying the number of signed contracts with the respective loadings would give the farmer’s total insurance costs net of indemnities. With this in mind, the picture is more balanced, even though the GDD derivative is still outperformed.

The bottom parts of Table 3 and Table 4 also include the realized standard deviation of the total gross margin for all analyzed water policy scenarios. Here, we distinguish between the ‘uninsured’ standard deviation that neglects the risk-reducing effect of the weather derivatives (if applicable) and the ‘insured’ standard deviation. While the ‘uninsured’ standard deviation with available weather derivatives is computed ex post, all other values are direct outcomes of the optimization process. Doing so reveals that the realized farm plans with weather derivatives tend to exhibit higher ‘uninsured’ standard deviations if compared to the farm plans without weather derivatives. This effect is particularly pronounced when it comes to a ban on irrigation with a surge from € 325/ha to € 431/ha in the ‘uninsured’ standard deviation. Thus, our results confirm the well-known phenomenon that agricultural insurance might augment risk taking i.e. that farmers incur additional production risk (cf., e.g. Turvey 2012).

4.2 Change in the certainty equivalent, expected value and standard deviation of the total gross margin

Figure 1 depicts the economic impact of the analyzed water policy settings which is measured as percentage change in the certainty equivalent in contrast to the base scenario. A systematic comparison of all water quota and water price scenarios with and without the availability of weather derivatives, respectively, provides the following results: Considering the scenarios without weather derivative first, it becomes clear that moderate cuts in the water quota, e.g. from 80 mm to 60 mm, and slight increases in the water price of up to € 0.5/mm involve only a minor decline of -2.1 % in the certainty equivalent in both cases. Moreover, the benefit of an unlimited irrigation water use in the € 0/mm scenario without weather derivative is rather small. On the contrary, a total ban on irrigation involves a sharp fall in the certainty equivalent. For a fair comparison, it should be noted that prohibitively high water prices would be required to induce a reduction in the farmer’s irrigation water use to 0 mm.

[Please insert Figure 1 about here.]

When considering the water policy scenarios in which weather derivatives can be applied, it becomes clear that the estimated certainty equivalents increase in all scenarios. In other words, the negative consequences of water use restrictions are mitigated. From a water policy impact perspective, purchasing weather derivatives enables the farmer to compensate for the loss in the certainty equivalent which results from a reduction in water quotas from e.g. 80 mm to 40 mm or from a boost in the water price to € 1.5/mm.

In addition to the base scenario comparison, Figure 2 reveals the percentage change in the certainty equivalent, the expected value and the standard deviation of the total gross margin resulting from the purchase of weather derivatives. Again, results are shown for all water policy settings under investigation. It becomes clear that the estimated certainty equivalents increase in all scenarios if weather derivatives are available. In this regard, the farmer's benefit is particularly pronounced in case of water quota reductions to 20 mm and 0 mm with a boost in the certainty equivalent of 15 % and of 19 %, respectively. Moreover, due to the cost of the additional insurance, the farm plans with weather derivatives exhibit a minor decline in the expected total gross margin in almost all scenarios. Only in case of a ban on irrigation, the farmer generates an additional expected total gross margin if weather derivatives are available. This is due to the possibility to further expand rainfed ware potato cropping which would otherwise expose risks that the farmer would not be willing to accept.

[Please insert Figure 2 about here.]

Furthermore, the realized farm plans with weather derivatives exhibit a sharp plunge in the standard deviation of the expected total gross margin for all water policy settings. In this regard, the whole-farm risk-reducing potential resulting from the purchase of the weather derivatives is quantified by the percentage change in the standard deviation of the expected total gross margin. Accordingly, the risk-reducing potential ranges from 17 % to 61 % in the analyzed scenarios.

5. Conclusions

Restrictive irrigation water policies for reasons of e.g. environmental concern or water scarcity appear to result in declining farm income and arising risk exposure. The purpose of this paper is to analyze the potential of index-based weather derivatives to cope with the economic disadvantages for farmers resulting from a reduction in water quotas or increased water prices. Based on the outcome of a whole-farm risk programming approach, we systematically compare crop portfolios without and with the possibility of purchasing standardized weather derivatives with underlying precipitation and temperature indices. Considering a representative cash crop farm situated in the northeastern part of the German region of Lower Saxony, the impact of weather derivatives on the irrigation water demand, certainty equivalents, as well as on the expected value and standard deviation of the total gross margins is estimated. Due to the explicit consideration of portfolio effects, we allow for crop diversification as well as for water reallocation patterns at the farm level; thus, overcoming some of the shortcomings inherent to previous work in this strand of research.

From a water policy perspective, the use of weather derivatives offsets the loss in the farmer's certainty equivalent resulting from moderate reductions in water quotas and water price increases. Moreover, our results also reveal that weather derivatives have the potential to substantially alter farm plans which might be accompanied by rising risk taking. In this regard, the effect of weather derivatives on the irrigation water demand remains ambiguous. We found substitution effects that result in a partial reduction in the applied amount of irrigation. However, these water-savings are, to a large extent, offset by a water reallocation towards production activities that would otherwise be provided with less or no irrigation. At the aggregated farm level, the provision of weather derivatives could even increase the optimal irrigation demand. This may have far reaching environmental implications which require further attention and careful consideration by policymakers.

The analysis is confined to normally distributed total gross margins. Although being a reasonable assumption in terms of portfolio optimization, an effective weather derivative which is set as option, appears to result in a right-skewed distribution since the probability of low outcomes in the left tail is systematically reduced (Musshoff et al. 2008). Thus, the total variability is falsely understood as systematic deviation from the mean. Consequently, we underestimate the risk-reducing potential of weather derivatives. In this regard, the consideration of downside risk measures appears to be interesting for future research (cf., e.g. Berg and Schmitz 2008).

In our example, weather indices are based on locally recorded weather data. We are aware that geographical basis risk may play a more pronounced role in other applications. However, the purpose of this study is to explore the interdependencies between the use of weather derivatives and the water demand at the farm level, and not to essentially contribute to the vast amount of literature on weather derivatives. Despite these limitations and without loss of generality, our approach highlights the need to consider diversification effects in the joint evaluation of irrigation and agricultural insurance in general as well as of weather derivatives in particular. Bearing in mind the rapid spread of agricultural insurance programs in recent years (Smith and Glauber 2012), there remains room for additional empirical evidence.

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Table 1 Production activities included in the whole-farm model†

Production activity		Expected gross margin (€/ha, €/contract)	Standard deviation (€/ha, €/contract)	Coefficient of variation	Applied irrigation (mm/ha)
Winter wheat	rainfed	374	217	0.58	0
	35 % AWC	660	161	0.24	77
	50 % AWC	637	172	0.27	139
Winter barley	rainfed	453	313	0.69	0
	35 % AWC	578	343	0.59	52
	50 % AWC	719	306	0.43	102
Ware potatoes	rainfed	2,118	1,509	0.71	0
	35 % AWC	3,806	1,291	0.34	73
	50 % AWC	4,137	1,202	0.29	132
Sugar beets	rainfed	1,152	613	0.53	0
	35 % AWC	1,582	332	0.21	72
	50 % AWC	1,594	305	0.19	137
Silage maize	rainfed	649	270	0.42	0
	35 % AWC	701	197	0.28	42
	50 % AWC	682	206	0.30	83
Weather derivatives‡	DD	-0.6	4	n/a	n/a
	GDD	-3.4	27	n/a	n/a

Note: † Computed from 10,000 bootstrap samples. ‡The strike levels K_{DD} and K_{GDD} are 47 dry days (DD) and 1014.6 °C (accumulated temperatures), respectively.

Table 2 Correlation matrix of the single gross margins†

	Wheat, rainfed	Wheat 35 % AWC	Wheat 50 % AWC	Barley, rainfed	Barley 35 % AWC	Barley 50% AWC	Potatoes, rainfed	Potatoes 35 % AWC	Potatoes 35 % AWC	Sugar beets, rainfed	Sugar beets 35 % AWC	Sugar beets 50 % AWC	Silage maize, rainfed	Silage maize 35 % AWC	Silage maize 50% AWC	DD weather derivative	GDD weather derivative
Wheat, rainfed	1.00																
Wheat 35 % AWC	0.88	1.00															
Wheat 50 % AWC	0.65	0.77	1.00														
Barley, rainfed	0.64	0.65	0.71	1.00													
Barley 35 % AWC	0.64	0.70	0.76	0.98	1.00												
Barley 50 % AWC	0.39	0.52	0.80	0.80	0.86	1.00											
Potatoes, rainfed	0.00	0.09	-0.03	-0.58	-0.47	-0.31	1.00										
Potatoes 35 % AWC	0.23	0.27	0.19	-0.34	-0.25	-0.12	0.90	1.00									
Potatoes 50 % AWC	0.37	0.40	0.37	-0.16	-0.07	0.05	0.81	0.97	1.00								
Sugar beets, rainfed	-0.11	0.08	0.39	-0.17	-0.07	0.27	0.54	0.57	0.59	1.00							
Sugar beets 35 % AWC	-0.14	-0.15	0.22	-0.19	-0.12	0.20	0.44	0.56	0.59	0.78	1.00						
Sugar beets 50 % AWC	-0.21	-0.16	0.27	0.05	0.12	0.40	0.12	0.25	0.30	0.72	0.87	1.00					
Silage maize, rainfed	-0.30	-0.19	-0.13	-0.68	-0.64	-0.37	0.64	0.42	0.33	0.43	0.22	-0.11	1.00				
Silage maize 35 % AWC	-0.27	-0.14	-0.10	-0.70	-0.63	-0.36	0.77	0.57	0.48	0.53	0.32	-0.01	0.97	1.00			
Silage maize 50 % AWC	-0.29	-0.16	-0.06	-0.67	-0.62	-0.34	0.74	0.56	0.47	0.61	0.38	0.08	0.93	0.97	1.00		
DD weather derivative	-0.13	-0.31	-0.14	0.05	-0.09	-0.11	-0.60	-0.69	-0.62	-0.42	-0.37	-0.24	-0.02	-0.18	-0.12	1.00	
GDD weather derivative	-0.21	-0.39	-0.75	-0.14	-0.18	-0.38	-0.26	-0.45	-0.46	-0.76	-0.59	-0.48	-0.41	-0.45	-0.57	0.02	1.00

Note: † Computed from 10,000 bootstrap samples.

Table 3 Crop-based activity levels in ha and the amount of signed weather derivatives in case of changing water quotas

Production activities†/ water quota scenarios	Without weather derivatives					With weather derivatives				
	80 mm	60 mm	40 mm	20 mm	0 mm	80 mm	60 mm	40 mm	20 mm	0 mm
Winter wheat, rainfed	0	0	11.7	7.1	19.9	0	0	0	6.1	6.1
Winter wheat 35 % AWC	13.6	11.7	0	0	0	11.7	11.7	8.9	0	0
Winter wheat 50 % AWC	0	0	0	0	0	0	0	0	0	0
Winter barley, rainfed	0	37.6	59.4	59.4	59.4	0	34.9	59.4	59.4	59.4
Winter barley 35 % AWC	18.7	0	0	0	0	4.7	5.5	0	0	0
Winter barley 50 % AWC	39.3	21.8	0	0	0	54.7	19.0	0	0	0
Ware potatoes, rainfed	0	0	0	0	31.1	0	0	0	0	45.0
Ware potatoes 35 % AWC	0	0	8.1	45.0	0	0	0	5.4	39.7	0
Ware potatoes 50 % AWC	45.0	45.0	36.9	0	0	45.0	45.0	39.6	5.3	0
Sugar beets, rainfed	0	0	0	24.4	29.8	0	0	14.6	29.8	29.8
Sugar beets 35 % AWC	12.4	24.2	24.2	4.4	0	24.2	24.2	12.3	0	0
Sugar beets 50 % AWC	11.2	0	0	0	0	0	0	0	0	0
Silage maize, rainfed	39.8	39.8	39.8	39.8	39.8	39.8	39.8	39.8	39.8	39.8
Silage maize 35 % AWC	0	0	0	0	0	0	0	0	0	0
Silage maize 50 % AWC	0	0	0	0	0	0	0	0	0	0
DD weather derivative	n/a	n/a	n/a	n/a	n/a	7,979	7,549	7,993	9,812	10,208
GDD weather derivative	n/a	n/a	n/a	n/a	n/a	1,275	1,178	1,284	1,475	1,184
Irrigation water demand (mm/ha)	80	60	40	20	0	80	60	40	20	0
Standard deviation ‘uninsured’ (€/ha)	360	354	345	384	325	371	354	363	391	431
Standard deviation ‘insured’ (€/ha)	n/a	n/a	n/a	n/a	n/a	205	199	187	151	270
Expected total gross margin (€/ha)	1,619	1,581	1,516	1,424	880	1,583	1,534	1,469	1,367	947
Certainty equivalent (€/ha)	1,377	1,348	1,293	1,148	683	1,504	1,460	1,403	1,324	812

Note: † Set-aside areas are not chosen in any scenario.

Table 4 Crop-based activity levels in ha and the amount of signed weather derivatives in case of increased water prices

Production activities†/ water price scenarios	Without weather derivatives					With weather derivatives				
	€ 0/mm	€ 0.5/mm	€ 1/mm	€ 1.5/mm	€ 2/mm	€ 0/mm	€ 0.5/mm	€ 1/mm	€ 1.5/mm	€ 2/mm
Winter wheat, rainfed	0	0	0	0	0	0	0	0	0	0
Winter wheat 35 % AWC	16.5	16.5	14.9	11.7	11.7	16.5	15.4	14.5	11.7	11.7
Winter wheat 50 % AWC	0	0	0	0	0	0	0	0	0	0
Winter barley, rainfed	0	0	0	32.4	59.4	0	0	0	0	0
Winter barley 35 % AWC	0	0	0	0.1	0	0	0	0	0	11.3
Winter barley 50 % AWC	59.4	59.4	57.3	26.9	0	59.4	59.4	59.4	59.4	48.1
Ware potatoes, rainfed	0	0	0	0	0	0	0	0	0	0
Ware potatoes 35 % AWC	0	0	0	0	0	0	0	0	0	0
Ware potatoes 50 % AWC	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0
Sugar beets, rainfed	0	0	0	0	0	0	0	0	0	0
Sugar beets 35 % AWC	0	0	0	24.2	24.2	0	24.2	24.2	24.2	24.2
Sugar beets 50 % AWC	23.0	23.0	23.0	0	0	23.0	0	0	0	0
Silage maize, rainfed	0	0	39.8	39.8	39.8	0	0	9.7	39.8	39.8
Silage maize 35 % AWC	36.1	36.1	0	0	0	36.1	36.1	27.3	0	0
Silage maize 50 % AWC	0	0	0	0	0	0	0	0	0	0
DD weather derivative	n/a	n/a	n/a	n/a	n/a	7,995	8,304	8,225	7,978	7,979
GDD weather derivative	n/a	n/a	n/a	n/a	n/a	1,201	1,248	1,257	1,284	1,261
Irrigation water demand (mm/ha)	100	100	89	63	48	100	91	89	81	78
Standard deviation 'uninsured' (€/ha)	361	361	360	356	344	361	373	373	373	369
Standard deviation 'insured' (€/ha)	n/a	n/a	n/a	n/a	n/a	199	205	205	206	203
Expected total gross margin (€/ha)	1,642	1,592	1,542	1,495	1,454	1,592	1,550	1,505	1,464	1,421
Certainty equivalent (€/ha)	1,398	1,349	1,300	1,258	1,233	1,519	1,471	1,426	1,385	1,344

Note: † Set-aside areas are not chosen in any scenario.

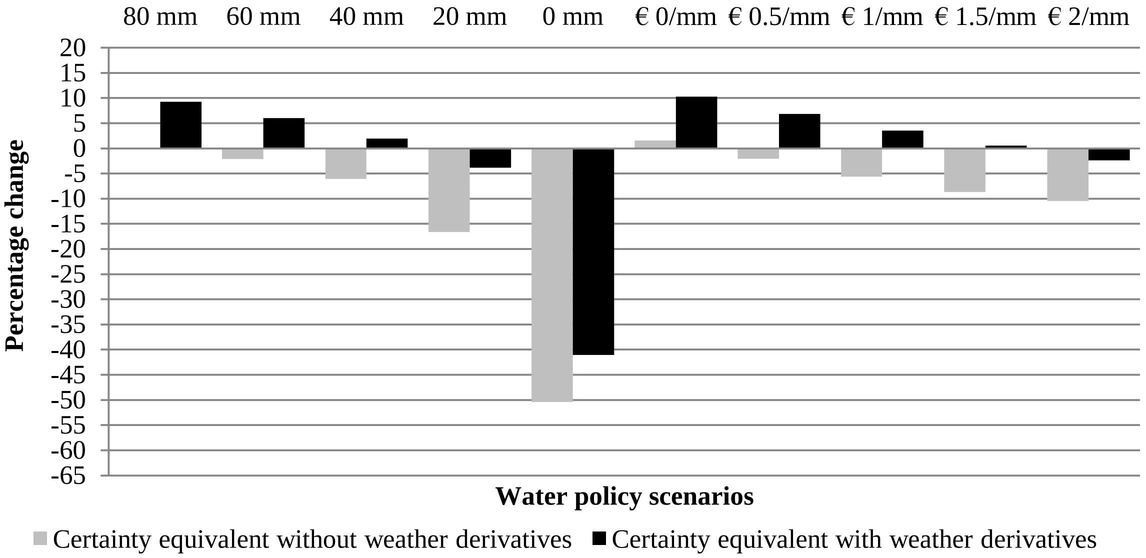

Figure 1 Percentage change in the certainty equivalent compared to the base scenario as a result of changing water policies. The base scenario refers to a granted water quota of 80 mm without the possibility to purchase weather derivatives.

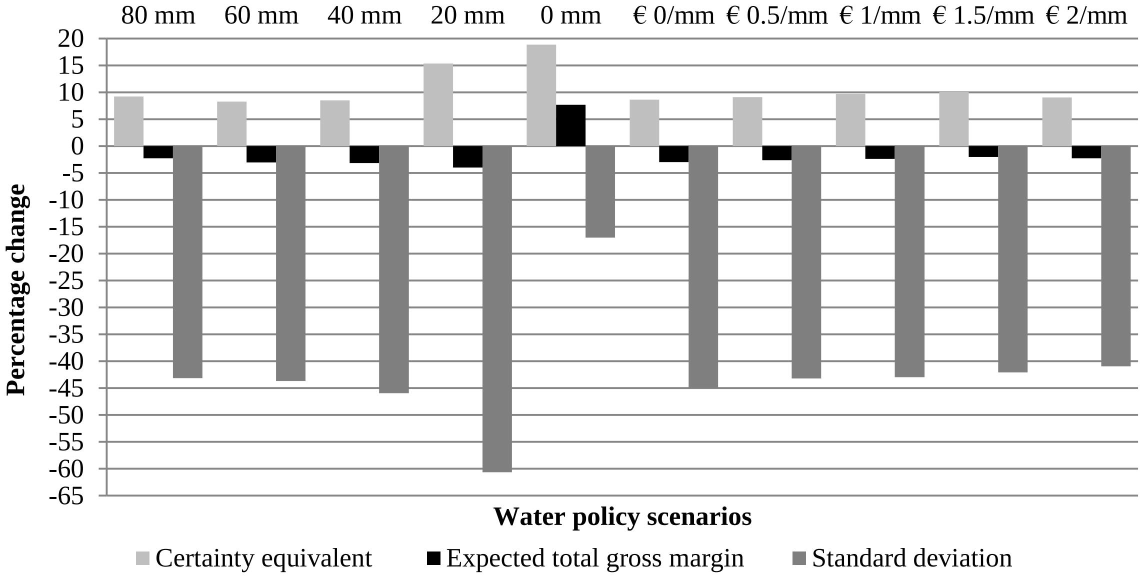

Figure 2 Percentage change in the certainty equivalent, expected value and standard deviation of the total gross margin compared to irrigation water policy scenarios without weather derivatives. The percentage change in the standard deviation results from the comparison of the 'uninsured' and 'insured' standard deviation for farm plans with weather derivatives being unavailable and available, respectively.