# **Online supplement**

## **S.I Index calculation and measurement period**

The index measurement period for all indices starts at day of year rti and ends at day of year Rit in accordance to the observed occurrence dates of the crop growth phases from stem elongation to a day before the entrance of milk ripeness for farm i in year t.

*Cumulative precipitation index (CPI) and standardized precipitation index (SPI)*

The realized value of the cumulative precipitation index is the sum of daily precipitation as shown in Eq. (S1).

|  |  |
| --- | --- |
|  | (S1) |

The standardized precipitation index (SPI) is the standardized form of the cumulative precipitation index with respect to the site-specific, long-term average of historical cumulative precipitation amounts measured during the flexible index measurement period. For the standardization procedure, we also use farm-specific cumulative precipitation amounts in the years of 1992 to 1994 to increase the sample and derive better estimates. We start in 1992 because this is the first year with reliable phenology reports that allow the calculation of a reliable index measurement period at farm-level. We derive the SPI-values by fitting for each farm a Gamma distribution with all available from 1992 to 2015 with the method of unbiased probability weighted moments. Subsequently, the Gamma distribution is transformed into a Gaussian distribution from which the realized values of the standardized precipitation index are derived. The SPI-values show the deviation from the site-specific long-term average in the units of standard deviations. As an example, the interpretation of a SPI-value equal to -1 is that the measured cumulative precipitation is one standard deviation below its expectation. As robustness checks, we fitted a Pearson III and log-logistic distribution with the available and additionally used the method of plotting position probability weighted moments. These robustness checks do not change our findings.

*Standardized precipitation evapotranspiration index (SPEI)*

The realized value of the standardized precipitation evapotranspiration index is the standardized value of the climatic water balance illustrated in Eq. (S2), where daily precipitation and potential evapotranspiration are denoted as and .

|  |  |
| --- | --- |
|  | (S2) |

We derive SPEI-values by fitting for each farm a log-logistic distribution[[1]](#footnote-2) for the available values of the climatic water balance from 1992 to 2015 with the method of unbiased probability weighted moments. The log-logistic distribution is subsequently transformed into a Gaussian distribution to derive the SPEI-values. The interpretation is the same as for the SPI. As robustness checks, we fitted a Pearson III and three parametric Gamma distribution with the available and additionally used the method of plotting position probability weighted moments for parameter estimation. These robustness checks do not change our findings.

*Soil moisture index (SMI)*

The realized value of the soil moisture index is the average of daily plant available soil moisture () for farm i and year t as illustrated in Eq. (S3). The daily plant available soil moisture is given in percentage of the plant available field capacity, which is the maximum amount of soil water available to plants.

|  |  |
| --- | --- |
|  | (S3) |

*Evaporative stress index (ESI)*

The realized values of the evaporative stress index are the standardized anomalies in the ratio of the sum of daily actual evapotranspiration to the sum of daily potential evapotranspiration . Therefore, we first calculate the water requirement satisfaction index for each farm and the years from 1992 to 2015 () following Eq. (S4).

|  |  |
| --- | --- |
|  | (S4) |

Subsequently, we transform the values to standardized anomalies following Eq. (S5), where is the site-specific, long-term average and the standard deviation of observed , respectively.

|  |  |
| --- | --- |
|  | (S5) |

*Length of the flexible index measurement period*

Winter wheat accumulates certain winter and spring temperature loads. After the completion of this process, called vernalization, crop growth mainly depends on temperatures, but also other weather variables and management decisions can have an influence (Gerstmann *et al.*, 2016). Winter wheat is especially vulnerable to droughts during its generative growth phases. Dalhaus, Musshoff and Finger (2018) find that the period from stem elongation to milk ripeness, as observed by regional phenology reporters, is best suited to insure wheat against drought in Germany. This approach of using observed phenology dates specifically accounts for the spatial heterogeneity in the timing of growth phases. Therefore, each farm receives an insurance that flexibly considers spatial and temporal differences in the start and end date of these growth phases. The distribution of the flexible length of the index measurement period is illustrated in Figure S1.

We choose the closest phenology reporter that is within the same region as the farm. If no appropriate phenology reporter is available for a specific farm and year, we use the average entrance dates of stem elongation and the average day before the entrance of milk ripeness of all other farms in this year to define start and end dates of the index measurement period.

**Figure S1:** Distribution of the flexible length of the index measurement period.

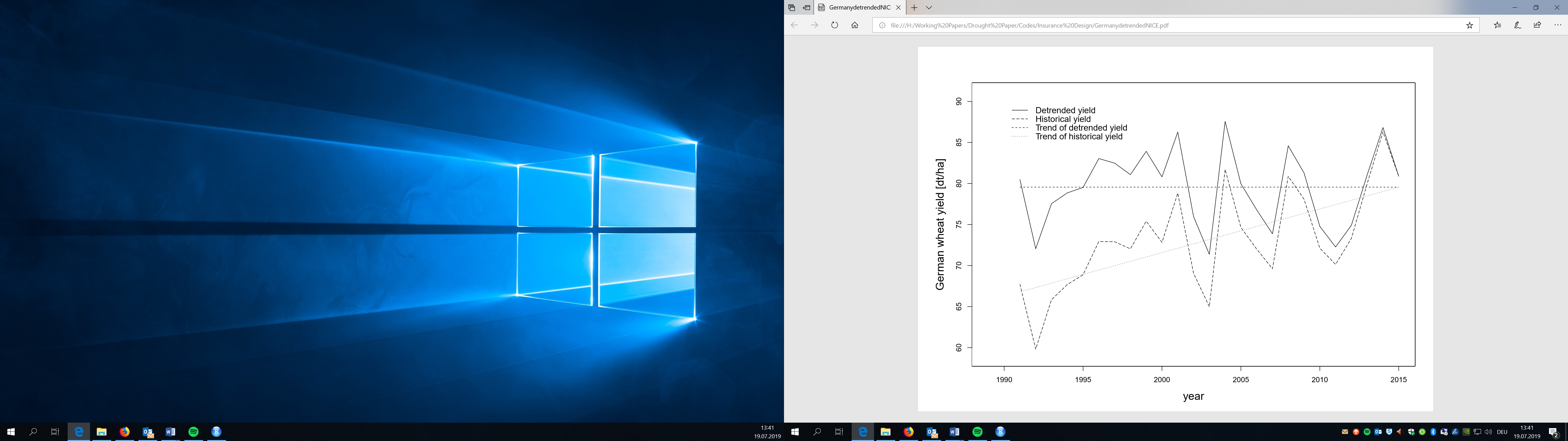
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## **S.2 Trend in wheat yields**

We remove deterministic trends in historical winter wheat yields and adjust earlier yield observation to the expected yield in 2015. Without detrending, earlier yield observations would be comparatively low due to a difference in technological conditions (e.g. genetics of wheat cultivars) and not necessarily due to drought occurrence, i.e. earlier observations without detrending cause an overestimation of yield variability and therewith bias the derivation of tick sizes, strike levels and risk-reducing potentials.

Farm-individual time series of yields are often too short and too volatile to capture technological trends underlying the production (Marra and Schurle, 1994). We therefore use national wheat yield observations after German reunification from 1991 to 2015 (FAO, 2019). Following Finger (2013), we use the robust M-estimator to identify a linear trend. The Akaike Information Criterion (AIC) favors a linear trend (AIC = 152.70) over a quadratic trend (AIC = 154.60). Figure S2 shows the national historical yields, the linear trend in historical yields with slope coefficient = 0.53 deci-tons per year and the detrended German wheat yields.

**Figure S2:** Detrending of German wheat yields.



We derive farm-individual detrended yields with Eq. (S6) by inserting = 0.53 and = 2015.

## **S.3 Additional information on contract specifics and historical payouts**

Table S1 summarizes the contract specifics for each underlying. Note that quantile regression does not always reveal a substantial drought risk. In this case, the slope coefficient (tick size) of index impacts is negative and results in a premium of 0 Euros per hectares, i.e. these farms would not be insured. Therefore, these uninsured farms that do not reveal a drought risk are not considered in Table S1. Using data of the insured farm only does not always result in realistic estimates of drought impacts. See S.10 “Cross-validation” for improving unrealistic estimates.

Figure S3 shows the historical payouts of each drought index and the non-uniform insurance product (where each farm receives the most risk-reducing underlying assuming moderate risk-aversion).

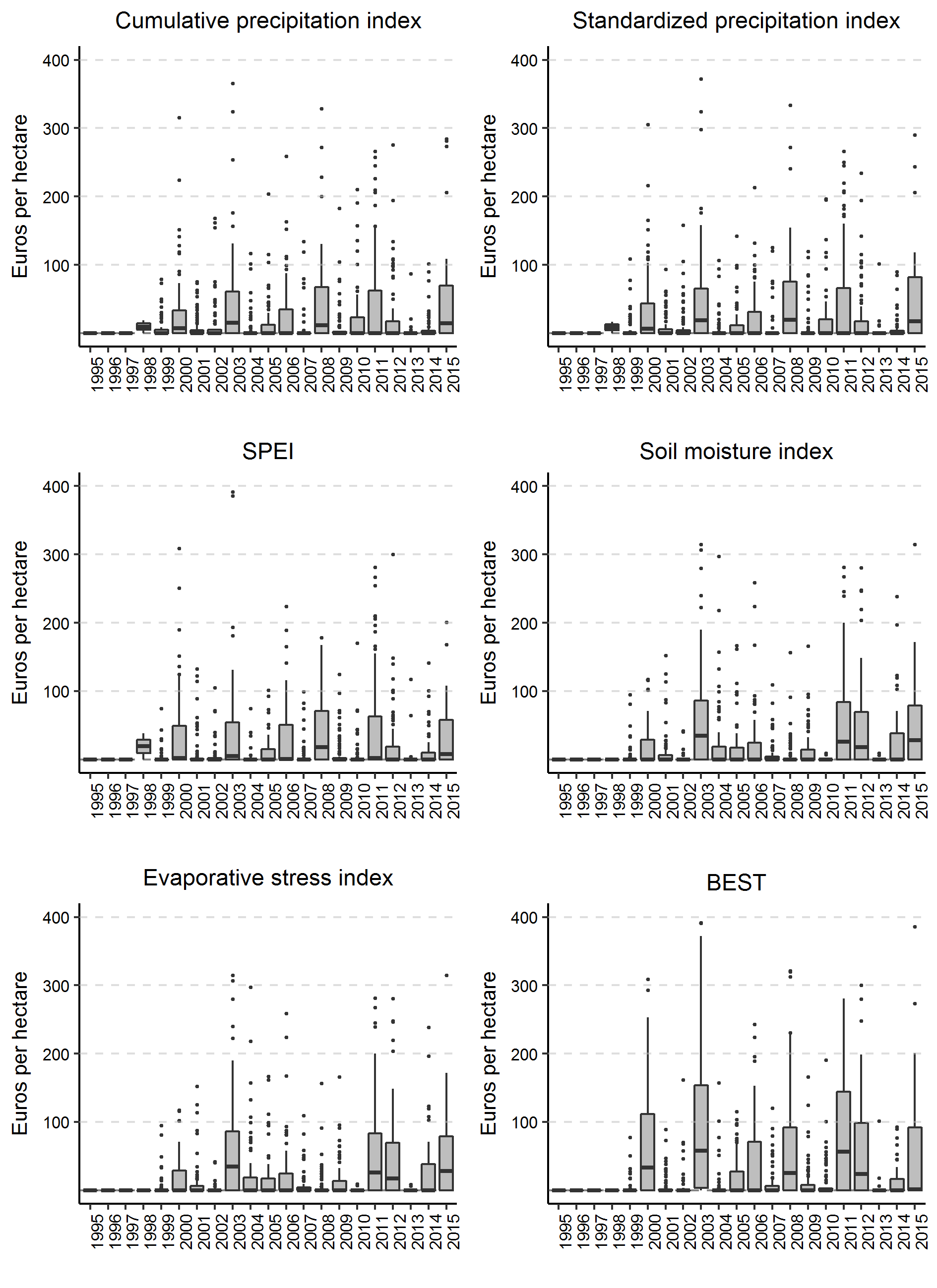
**Table S1.**

Summary statistics of contract specifics.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Underlying** | **Statistics** | **Tick size**  **[deci-ton / index unit]** | **Strike level**  **[index unit]** | **Premium**  **[Euros / hectare]** |
| **CPI**  **[mm]** | **min** | 0.00 | 42.10 | 0.00 |
| **median** | 0.07 | 126.13 | 19.58 |
| **mean** | 0.08 | 130.53 | 29.93 |
| **max** | 0.32 | 271.80 | 167.54 |
|  | **sd** | 0.07 | 47.80 | 33.63 |
| **SPI**  **[sd]** | **min** | 0.15 | -1.90 | 0.00 |
| **median** | 2.97 | -0.07 | 19.12 |
| **mean** | 3.94 | -0.01 | 29.05 |
| **max** | 15.09 | 2.37 | 134.32 |
|  | **sd** | 3.21 | 0.84 | 29.48 |
| **SPEI**  **[sd]** | **min** | 0.08 | -1.10 | 0.04 |
| **median** | 3.19 | 0.05 | 25.88 |
| **mean** | 4.00 | 0.12 | 31.47 |
| **max** | 18.07 | 1.81 | 151.69 |
|  | **sd** | 3.50 | 0.63 | 30.51 |
| **SMI**  **[%]** | **min** | 0.02 | 55.00 | 0.09 |
| **median** | 0.37 | 69.68 | 19.97 |
| **mean** | 0.43 | 69.40 | 30.88 |
| **max** | 1.34 | 87.89 | 151.45 |
|  | **sd** | 0.31 | 7.55 | 34.97 |
| **ESI**  **[sd]** | **min** | 0.06 | -1.73 | 0.00 |
| **median** | 4.35 | -0.09 | 25.01 |
| **mean** | 4.74 | -0.17 | 33.97 |
| **max** | 13.72 | 1.36 | 128.84 |
|  | **sd** | 3.52 | 0.73 | 31.88 |

*Notes:* Cumulative precipitation index (CPI) is measured in millimeter [mm], standardized precipitation index (SPI) in standard deviations [sd], standardized precipitation evapotranspiration index (SPEI) in standard deviations [sd], soil moisture index (SMI) in average plant available soil moisture in percentage [%] to maximum plant available soil moisture and evaporative stress index (ESI) in standard deviations [sd]. Statistics only for farms with premium > 0, which is the case for 60 farms with the CPI, 61 farms with the SPI, 54 with the SPEI, 59 for the SMI and 68 for the ESI. Numbers are rounded to two decimal places.

**Figure S3:** Historical payouts.



*Notes*: BEST evaluated with expected utility model assuming moderately risk-averse farmers ( =2).

## **S.4 Spatial distribution of BEST**

Figure S4 shows natural regions that share a similar ecosystem in Germany. The symbols illustrate the farm locations as well as the most risk reducing underlying evaluated for moderately risk-averse farmers (. The colors display the relative risk reduction for the non-uniform insurance product (BEST) in which each farm receives the most risk-reducing underlying compared to the uninsured status. There is no clear spatial clustering of the best underlying. The largest relative risk reductions take place near the border to Poland in the North German Plain.

Similarly, the colors of symbols in Figure S5 show the actuarially fair premium. There is no clear spatial clustering of the premium, but a slight tendency to increase from the sea to further inland. Farmers who experience a large relative risk reduction (shown in Figure S4) often have a comparatively large actuarially fair premium (shown in Figure S5). This shows that large risk reductions do usually not result from low premiums, but from the weather index insurance’s ability to compensate losses accurately.

Accordingly, when qualitatively comparing Figure 6 of Lüttger and Feike (2018) to regions of highest risk reduction in Figure S4 in our sample, weather index insurance is especially suited to cover losses in regions with large yield volatility.

**Figure S4:** Map of natural regions in Germany and the best drought index for each farm with its relative risk reduction assuming moderate risk-aversion (.

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*Notes: CPI* is the cumulative precipitation index, *SPI* the standardized precipitation index, *SPEI* the standardized precipitation evapotranspiration index, *SMI* the soil moisture index and *ESI* the evaporative stress index. Best drought index evaluated for moderately risk-averse farmers (=2).

**Figure S5:** Map of natural regions in Germany and the best drought index for each farm with its premium assuming moderate risk-aversion (.



*Notes: CPI* is the cumulative precipitation index, *SPI* the standardized precipitation index, *SPEI* the standardized precipitation evapotranspiration index, *SMI* the soil moisture index and *ESI* the evaporative stress index. Best drought index evaluated for moderately risk-averse farmers (=2).

## **S.5 Expected utility model: Additional information and robustness checks**

This section provides additional information and robustness checks for the expected utility model. Table S2 shows the composition of the non-uniform insurance product (each farm receives the most risk-reducing underlying) assuming slightly (=0.5) or extremely (=4) risk-averse farmers. The composition of the non-uniform insurance product (BEST) only change slightly across different levels of risk aversion.

**Table S2.**

Composition of the non-uniform insurance product (BEST) for slightly ( =0.5) and extremely risk-averse (=4) farmers.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | **CPI** | **SPI** | **SPEI** | **SMI** | **ESI** | **Uninsured** |
| **0.5** | 5 | 12 | 8 | 12 | 32 | 16 |
| **4** | 7 | 12 | 10 | 13 | 28 | 15 |

Notes**:** 85 farms covered. Uninsured means that there is no index causing a lower risk premium than the uninsured status. is the coefficient of constant relative risk aversion used in Eq. (8) of the paper, CPI the cumulative precipitation index, SPI the standardized precipitation index, SPEI the standardized precipitation evapotranspiration index, SMI the soil moisture index and ESI the evaporative stress index.

Table S3 shows average absolute and relative reductions in the risk premium for slightly (=0.5) and extremely (=4) risk-averse farmers as well as their significance levels. The corresponding p-values of Wilcoxon signed rank tests are depicted in Table S4. For both types of risk-aversion, all of the here considered indices have, on average, a significantly lower risk premium (lower risk exposure) than the uninsured status. The evaporative stress index has, on average, the significantly lowest risk premium (lowest basis risk) considering only uniform insurance products (each farm receives the same underlying drought index). However, the non-uniform insurance product (each farm receives its most risk reducing index) has, on average, the significantly lowest risk premium (lowest basis risk). Table S5 shows the number of farms that experience a risk reduction for each underlying and coefficient of constant relative risk aversion (). Table S6 shows the summary statistics for relative changes in the risk premiums for each index and coefficient of constant relative risk aversion (. Results show that average risk reductions increase in the level of risk-aversion. Moreover, Table S5 and S6 show that not all farms experience a risk reduction with uniform insurance products. The maximum relative risk increase (18.73% for an extremely risk-averse farmer with the soil moisture index (SMI)) is much lower than the maximum relative risk reduction (75.68% for an extremely risk-averse farmer with the evaporative stress index (ESI)). With exception of the standardized precipitation evapotranspiration index (SPEI), there is a risk reduction at the median for each drought index. The on average and at the median largest risk reductions result for the non-uniform insurance.

**Table S3.**

Absolute (in ‎€/ha) and in parentheses relative (in %) average differences in the risk premium (RP) and their significance for slightly (=0.5) and extremely (=4) risk-averse farmers.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  |  |  | | **RPn** | | | |
|  |  | **m/n** | **CPI** | **SPI** | **SPEI** | **SMI** | **ESI** | **Uninsured** |
| **RPm** | **0.5** | **CPI** | --- |  |  |  |  | **-0.56\*\*\***  **(-6.87)** |
| **SPI** | -0.03  (-0.26) | --- |  |  |  | **-0.60\*\*\***  **(-7.24)** |
| **SPEI** | 0.06  (2.07) | 0.10  (2.38) | --- |  |  | **-0.50\*\*\***  **(-5.74)** |
| **SMI** | -0.04  (1.57) | 0.00  (1.83) | -0.10  (1.25) | --- |  | **-0.60\*\*\***  **(-6.91)** |
| **ESI** | **-0.50\*\*\***  **(-5.92)** | **-0.46\*\*\***  **(-5.61)** | **-0.56\*\*\***  **(-7.12)** | **-0.46\*\*\***  **(-6.25)** | --- | **-1.06\*\*\***  **(-12.40)** |
| **BEST** | **-0.70\*\*\***  **(-9.55)** | **-0.67\*\*\***  **(-9.26)** | **-0.76\*\*\***  **(-10.49)** | **-0.66\*\*\***  **(-9.80)** | **-0.20\*\*\***  **(-3.49)** | **-1.26\*\*\***  **(-15.58)** |
| **4** | **CPI** | --- |  |  |  |  | **-5.71\*\*\***  **(-7.71)** |
| **SPI** | -0.37  (-0.56) | --- |  |  |  | **-6.08\*\*\***  **(-8.37)** |
| **SPEI** | 0.26  (2.31) | 0.62  (3.05) | --- |  |  | **-5.45\*\*\***  **(-6.79)** |
| **SMI** | -2.02  (0.50) | -1.66  (1.16) | -2.28  (0.77) | --- |  | **-7.73\*\*\***  **(-9.01)** |
| **ESI** | **-5.78\*\*\***  **(-7.20)** | **-5.41\*\***  **(-6.52)** | **-6.04\*\*\***  **(-8.18)** | **-3.76\*\***  **(-6.66)** | --- | **-11.49\*\*\***  **(-14.49)** |
| **BEST** | **-8.32\*\*\***  **(-11.76)** | **-7.95\*\*\***  **(-11.15)** | **-8.58\*\*\***  **(-12.51)** | **-6.30\*\*\***  **(-11.11)** | **-2.54\*\*\***  **(-4.39)** | **-14.03\*\*\***  **(-18.40)** |

Notes: Numbers without brackets display the absolute average reduction in the risk premium (RPm – RPn) in Euros per hectare (€/ha) of winter wheat. Numbers in brackets display the relative average reduction in the risk premium in percentage ((RPm – RPn) / RPn). Numbers are rounded to two decimal places. Asterisks show the Bonferroni-adjusted significance level derived from one-sided paired Wilcoxon signed rank tests: \* at the 1% level, \*\* at the 0.2% level and \*\*\* at the 0.02% level. Null hypotheses tested are RPm ≥ RPn. Significant differences are highlighted in bold. Absolute risk premium without holding any insurance is on average 6.59 Euros per hectare for slightly risk-averse farmers and 59.73 Euros per hectare for extremely risk-averse farmers. is the coefficient of constant relative risk aversion used in Eq. (8) in the paper, CPI the cumulative precipitation index, SPI the standardized precipitation index, SPEI the standardized precipitation evapotranspiration index, SMI the soil moisture index and ESI the evaporative stress index.

**Table S4.**

P-values of one-sided Wilcoxon signed rank tests for different coefficients of constant relative risk aversion .

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  | |  | **RPn** | | | | | |
|  |  | **m/n** | | **CPI** | **SPI** | **SPEI** | **SMI** | **ESI** | **Uninsured** |
| **0.5** | **RPm** | **CPI** | | --- |  |  |  |  | 1.02E-07 |
| **SPI** | | 1.20E-01 | --- |  |  |  | 5.26E-08 |
| **SPEI** | | 9.31E-01 | 9.48E-01 | --- |  |  | 1.60E-05 |
| **SMI** | | 4.01E-01 | 5.88E-01 | 7.82E-02 | --- |  | 2.58E-08 |
| **ESI** | | 6.26E-05 | 5.37E-05 | 3.40E-07 | 6.46E-05 | --- | 1.12E-10 |
| **BEST** | | 5.73E-13 | 8.36E-12 | 2.65E-12 | 2.65E-12 | 3.94E-09 | 2.67E-13 |
| **2** | **RPm** | **CPI** | | --- |  |  |  |  | 1.90E-07 |
| **SPI** | | 1.70E-01 | --- |  |  |  | 5.26E-08 |
| **SPEI** | | 8.63E-01 | 9.35E-01 | --- |  |  | 1.86E-05 |
| **SMI** | | 3.03E-01 | 4.86E-01 | 9.12E-02 | --- |  | 1.36E-08 |
| **ESI** | | 1.03E-04 | 1.08E-04 | 1.80E-06 | 1.82E-04 | --- | 1.63E-10 |
| **BEST** | | 1.23E-12 | 8.36E-12 | 3.88E-12 | 3.88E-12 | 1.82E-09 | 3.91E-13 |
| **4** | **RPm** | **CPI** | | --- |  |  |  |  | 4.07E-07 |
| **SPI** | | 1.40E-01 | --- |  |  |  | 7.62E-08 |
| **SPEI** | | 8.05E-01 | 9.21E-01 | --- |  |  | 9.74E-06 |
| **SMI** | | 1.72E-01 | 3.18E-01 | 1.25E-01 | --- |  | 5.90E-09 |
| **ESI** | | 1.96E-04 | 2.63E-04 | 1.80E-05 | 3.93E-04 | --- | 7.56E-10 |
| **BEST** | | 8.40E-13 | 8.36E-12 | 3.88E-12 | 3.88E-12 | 8.42E-10 | 1.82E-13 |

Notes: Null hypotheses tested are RPm ≥ RPn. is the coefficient of constant relative risk aversion used in Eq. (8) in the paper, CPI the cumulative precipitation index, SPI the standardized precipitation index, SPEI the standardized precipitation evapotranspiration index, SMI the soil moisture index and ESI the evaporative stress index.

**Table S5.**

Number of farms experiencing a reduction in risk premium depending on drought index and coefficient of constant relative risk aversion ().

|  |  |  |  |
| --- | --- | --- | --- |
| **Underlying** |  | | |
|  | **0.5** | **2** | **4** |
| **CPI** | 47 | 47 | 46 |
| **SPI** | 49 | 48 | 48 |
| **SPEI** | 41 | 39 | 40 |
| **SMI** | 50 | 48 | 50 |
| **ESI** | 57 | 57 | 55 |
| **BEST** | 69 | 68 | 70 |

Notes:Sample contains 85 farms. is the coefficient of constant relative risk aversion used in Eq. (8) in the paper, CPI the cumulative precipitation index, SPI the standardized precipitation index, SPEI the standardized precipitation evapotranspiration index, SMI the soil moisture index and ESI the evaporative stress index.

**Table S6.**

Summary statistics of relative changes in the risk premiums compared to being uninsured and in percentages [%] for different coefficients of constant relative risk aversion ().

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | **Underlying** | **Min** | **Median** | **Mean** | **Max** | **SD** |
| **0.5** | **CPI** | -56.33 | -0.91 | -6.87 | 11.87 | 12.39 |
| **SPI** | -57.03 | -1.02 | -7.24 | 8.82 | 12.07 |
| **SPEI** | -70.41 | 0.00 | -5.74 | 16.85 | 13.68 |
| **SMI** | -42.02 | -2.29 | -6.91 | 15.41 | 10.81 |
| **ESI** | -68.72 | -6.72 | -12.40 | 11.59 | 17.12 |
| **BEST** | -70.41 | -11.25 | -15.58 | 0.00 | 16.95 |
| **2** | **CPI** | -60.65 | -0.97 | -7.30 | 12.34 | 13.13 |
| **SPI** | -61.85 | -1.37 | -7.79 | 8.00 | 12.78 |
| **SPEI** | -71.95 | 0.00 | -6.25 | 14.93 | 14.42 |
| **SMI** | -45.09 | -2.41 | -7.92 | 16.83 | 12.05 |
| **ESI** | -71.39 | -7.63 | -13.41 | 11.52 | 18.21 |
| **BEST** | -71.95 | -12.88 | -16.89 | 0.00 | 18.02 |
| **4** | **CPI** | -64.22 | -0.92 | -7.71 | 13.24 | 13.88 |
| **SPI** | -65.71 | -1.25 | -8.37 | 9.87 | 13.58 |
| **SPEI** | -73.54 | 0.00 | -6.79 | 11.95 | 15.22 |
| **SMI** | -48.93 | -3.18 | -9.01 | 18.73 | 13.45 |
| **ESI** | -75.68 | -7.38 | -14.49 | 11.34 | 19.55 |
| **BEST** | -75.67 | -14.12 | -18.40 | 0.00 | 19.27 |

Notes: Values display the summary statistics for relative changes in the risk premium with underlying k compared to the uninsured status and are in percentages [%] ((RPk – RPuninsured) / RPuninsured). Negative values show a reduction in the risk premium (i.e. risk exposure). Positive values show an increase in the risk premium (i.e. risk exposure). is the coefficient of constant relative risk aversion used in Eq. (8) in the paper, CPI the cumulative precipitation index, SPI the standardized precipitation index, SPEI the standardized precipitation evapotranspiration index, SMI the soil moisture index and ESI the evaporative stress index.

## **S.6 Adding a premium load**

This section presents the results when we add a loading on the actuarially fair premium, which causes shifts in the expected wealth. Therefore, we cannot use the risk premium as risk measure because a comparison in risk premiums requires the same expected wealth in each sample (Chavas, 2004). In this section, we report changes in the certainty equivalent, which is the sure amount of money that results in the same utility as the expected utility from a risky activity as illustrated in Eq. (S7) (Di Falco and Chavas, 2009). The certainty equivalent for farm i with underlying k is derived by inserting the expected utility of random wealth across all years t into the inverse utility function . We use the utility function depicted in Eq. (8) in the main manuscript and assume moderately risk-averse farmers (=2). Farmers prefer the underlying with the largest certainty equivalent, equivalent to the underlying with the largest expected utility (Berg, Quirion and Sultan, 2009).

Table S7 shows the composition of the non-uniform insurance product (BEST) for moderately risk-averse farmers (=2) when we add a loading of 10% or 20% on the actuarially fair premium. For both loadings, there is not a single drought index resulting in the largest certainty equivalent for each farm and the number of farms that are no better off with an insurance increases with an increase in the loading. For instance, a loading of 20% results in 58 farms (approximately two thirds of the sample size) that are no better off with any underlying. Table S8 shows absolute and relative changes[[2]](#footnote-3) in the certainty equivalent and Table S9 depicts the corresponding p-values for the null hypotheses that the certainty equivalents CEm are equal to, or smaller, than the certainty equivalents CEn. To illustrate, if all farms use the evaporative stress index (ESI) as underlying, the certainty equivalent increases, on average, by 2.18 Euros per hectare (+0.24%) compared to the uninsured status when there is a loading of 10% on the actuarially fair premium. For the 10% loading, all underlying drought indices have, on average, an increase in the certainty equivalent, but this effect is not significant for uniform insurance products, where each farm receives the same underlying. For the 20% loading, farmers have ,on average, a reduction in the certainty equivalent with uniform insurance products (i.e. are on average worse off with insurance), but about a third still experiences an increase in the certainty equivalent as shown in Table S7[[3]](#footnote-4). On average, the evaporative stress index (ESI) has a significantly larger certainty equivalent than the cumulative precipitation index (CPI), standardized precipitation index (SPI) and the standardized precipitation evapotranspiration index (SPEI) when there is a loading of 10%. No uniform insurance product has a significantly larger certainty equivalent when compared to each other for a loading of 20%. The non-uniform insurance product (BEST) has a significantly larger certainty equivalent than uniform insurance products and being uninsured for a 10% and 20% loading, respectively.

Overall, this robustness check confirms our key-findings. Regarding the overall risk reduction, these results imply that under expected utility there is little room to load the actuarially fair premium.

**Table S7.**

Composition of the non-uniform insurance product (BEST) when the actuarially fair premium has an additional loading and farmers are moderately risk-averse (=2).

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Loading** | **CPI** | **SPI** | **SPEI** | **SMI** | **ESI** | **Uninsured** |
| **10%** | 3 | 9 | 4 | 16 | 18 | 35 |
| **20%** | 2 | 4 | 1 | 14 | 6 | 58 |

Notes**:** 85 farms covered. Uninsured means that there is no index causing a lower risk premium than the uninsured status. is the coefficient of constant relative risk aversion used in Eq. (8) in the paper, CPI is the cumulative precipitation index, SPI the standardized precipitation index, SPEI the standardized precipitation evapotranspiration index, SMI the soil moisture index and ESI the evaporative stress index.

**Table S8.**

Absolute (in ‎€/ha) and in parentheses relative (in %) average differences in the certainty equivalent (CE) and their significance with a loading on the actuarially fair premium for moderately risk-averse farmers (=2).

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | | |  | **CEn** | | | | | |
| **Loading**  **[%]** |  | **m/n** | | **CPI** | **SPI** | **SPEI** | **SMI** | **ESI** | **Uninsured** |

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **10** | **CEm** | **CPI** | --- |  |  |  |  | 0.39  (0.05) |
| **SPI** | 0.18  (0.02) | --- |  |  |  | 0.57  (0.07) |
| **SPEI** | -0.09  (-0.01) | -0.27  (-0.03) | --- |  |  | 0.29  (0.04) |
| **SMI** | 0.49  (0.05) | 0.31  (0.04) | 0.59  (0.06) | --- |  | 0.88  (0.10) |
| **ESI** | **1.79\***  (0.19) | **1.61\***  (0.17) | **1.89\*\***  (0.19) | 1.30  (0.14) | --- | 2.18  (0.24) |
| **BEST** | **2.76\*\*\***  (0.28) | **2.58\*\*\***  (0.26) | **2.85\*\*\***  (0.29) | **2.26\*\*\***  (0.23) | **0.97\*\*\***  (0.09) | **3.14\*\*\***  (0.33) |
| **20** | **CEm** | **CPI** | --- |  |  |  |  | -1.79  (-0.15) |
| **SPI** | 0.20  (0.02) | --- |  |  |  | -1.59  (-0.13) |
| **SPEI** | 0.03  (0.00) | -0.18  (-0.02) | --- |  |  | -1.77  (-0.16) |
| **SMI** | 0.46  (0.05) | 0.25  (0.03) | 0.43  (0.05) | --- |  | -1.34  (-0.11) |
| **ESI** | 1.19  (0.13) | 0.98  (0.11) | 1.16  (0.13) | 0.73  (0.09) | --- | -0.61  (-0.02) |
| **BEST** | **3.46\*\*\***  (0.34) | **3.26\*\*\***  (0.32) | **3.43\*\*\***  (0.34) | **3.00\*\*\***  (0.30) | **2.27\*\*\***  (0.21) | **1.66\*\*\***  (0.19) |

Notes:Numbers without brackets display the absolute average reduction in the risk premium (CEm – CEn) in Euros per hectare (€/ha) of winter wheat. Numbers in brackets display the relative average reduction in the risk premium in percentage ((CEm – CEn) / CEn). Numbers are rounded to two decimal places. Asterisks show the Bonferroni-adjusted significance level derived from one-sided paired Wilcoxon signed rank tests: \* at the 1% level, \*\* at the 0.2% level and \*\*\* at the 0.02% level. Null hypotheses tested are CEm ≤ CEn. Significant differences are highlighted in bold. is the coefficient of constant relative risk aversion used in Eq. (8) in the paper, CPI the cumulative precipitation index, SPI the standardized precipitation index, SPEI the standardized precipitation evapotranspiration index, SMI the soil moisture index and ESI the evaporative stress index.

**Table S9.**

P-values of the one-sided Wilcoxon signed rank tests with a loading on the actuarially fair premium and for moderately risk-averse farmers (=2).

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  | |  | **CEn** | | | | | |
| **Loading [%]** |  | **m/n** | | **CPI** | **SPI** | **SPEI** | **SMI** | **ESI** | **Uninsured** |

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **10** | **CEm** | **CPI** | --- |  |  |  |  | 9.39E-01 |
| **SPI** | 4.21E-02 | --- |  |  |  | 7.41E-01 |
| **SPEI** | 7.48E-01 | 8.25E-01 | --- |  |  | 9.43E-01 |
| **SMI** | 1.29E-01 | 2.38E-01 | 6.67E-02 | --- |  | 3.57E-01 |
| **ESI** | 3.59E-03 | 5.59E-03 | 8.43E-04 | 6.68E-02 | --- | 4.46E-02 |
| **BEST** | 8.36E-12 | 8.36E-11 | 1.23E-11 | 8.42E-10 | 1.80E-10 | 3.90E-10 |
| **20** | **CEm** | **CPI** | --- |  |  |  |  | 1.00E-00 |
| **SPI** | 2.58E-02 | --- |  |  |  | 1.00E-00 |
| **SPEI** | 5.07E-01 | 5.59E-01 | --- |  |  | 1.00E-00 |
| **SMI** | 1.27E-01 | 2.03E-01 | 2.91E-01 | --- |  | 1.00E-00 |
| **ESI** | 3.77E-02 | 8.45E-02 | 8.73E-02 | 6.42E-01 | --- | 1.00E-00 |
| **BEST** | 1.80E-11 | 2.64E-11 | 1.80E-11 | 1.82E-09 | 5.70E-12 | 2.97E-06 |

Notes: Null hypotheses tested are CEm ≤ CEn. is the coefficient of constant relative risk aversion used in Eq. (8) in the paper, CPI the cumulative precipitation index, SPI the standardized precipitation index, SPEI the standardized precipitation evapotranspiration index, SMI the soil moisture index and ESI the evaporative stress index.

## **S.7 Quantile regression: Robustness check**

In this section, we tailor the index-yield relationship to the 20% quantiles of yield distributions, i.e. we change τ in the quantile regression estimator to 0.2 and use the corresponding 20% quantile of the yield distribution to derive the strike level and tick size (see section 2.2 in the main manuscript for further details on the estimation procedure).

The here presented results are showing changes in the risk premium assuming moderately risk-averse farmers. Table S10 shows the compositions of BEST, Table S11 average differences in the risk premium as well as their significance and Table S12 provides summary statistics of relative risk reductions. The results show that when focusing on the 20% quantile of yields, our results regarding the performance of the different indices compared to each other stays largely constant compared to the main results. Using the 20% quantile focuses on more extreme risks and reduces the overall risk reducing capacity compared to the 30% quantile because the strike level is adjusted downwards, i.e. moderate risks are no longer insured (see section 2.2 in the main manuscript for further details on the calculation of the strike level).

**Table S10.**

Composition of the non-uniform insurance (BEST) for the 20% quantile of interest and moderately risk-averse farmers (=2).

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Quantile** | **CPI** | **SPI** | **SPEI** | **SMI** | **ESI** | **Uninsured** |
| **20%** | 6 | 10 | 11 | 15 | 31 | 12 |

Notes: is the coefficient of constant relative risk aversion used in Eq. (8) in the paper, CPI the cumulative precipitation index, SPI the standardized precipitation index, SPEI the standardized precipitation evapotranspiration index, SMI the soil moisture index and ESI the evaporative stress index.

**Table S11.**

Absolute (in ‎€/ha) and in parentheses relative (in %) average differences in the risk premium (RP) and their significance for moderately risk-averse farmers (=2) when insurance is tailored to the 20% quantile of farm-yields.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
|  |  | **RPn** | | | | | |
|  | **m/n** | **CPI** | **SPI** | **SPEI** | **SMI** | **ESI** | **Uninsured** |
| **RPm** | **CPI** | --- |  |  |  |  | **-2.35\*\*\***  **(-6.54)** |
| **SPI** | -0.36  (-1.23) | --- |  |  |  | **-2.70\*\*\***  **(-7.40)** |
| **SPEI** | 0.13  (1.53) | 0.49  (3.14) | --- |  |  | **-2.22\*\*\***  **(-5.51)** |
| **SMI** | -0.38  (0.21) | -0.02  (1.92) | -0.51  (-0.85) | --- |  | **-2.73\*\*\***  **(-6.87)** |
| **ESI** | **-1.72\*\***  **(-4.58)** | **-1.37\*\***  **(-3.38)** | **-1.85\*\*\***  **(-5.92)** | **-1.34\*\*\***  **(-4.72)** | --- | **-4.07\*\*\***  **(-10.86)** |
| **BEST** | **-2.86\*\*\***  **(-9.08)** | **-2.50\*\*\***  **(-7.95)** | **-2.98\*\*\***  **(-9.94)** | **-2.48\*\*\***  **(-8.77)** | **-1.13\*\*\***  **(-3.99)** | **-5.20\*\*\***  **(-14.68)** |

Notes:Numbers without brackets display the absolute average reduction in the risk premium (RPm – RPn) in Euros per hectare (€/ha) of winter wheat. Numbers in brackets display the relative average reduction in the risk premium in percentage ((RPm – RPn) / RPn). Numbers are rounded to two decimal places. Asterisks show the Bonferroni-adjusted significance level derived from one-sided paired Wilcoxon signed rank tests: \* at the 1% level, \*\* at the 0.2% level and \*\*\* at the 0.02% level. Null hypotheses tested are RPm ≥ RPn. Significant differences are highlighted in bold. Quantile represents the yield quantile of interests τ in the quantile regression estimator to derive tick size and strike level. is the coefficient of constant relative risk aversion used in Eq. (8) in the paper, CPI the cumulative precipitation index, SPI the standardized precipitation index, SPEI the standardized precipitation evapotranspiration index, SMI the soil moisture index and ESI the evaporative stress index.

**Table S12.**

Summary statistics of contract specifics tailored to the 20% quantile of interest.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Underlying** | **Statistics** | **Tick size**  **[deci-ton / index unit]** | **Strike level**  **[index unit]** | **Premium**  **[Euros / hectare]** |
| **CPI**  **[mm]** | **min** | 0.00 | 44.59 | 0.21 |
| **median** | 0.08 | 122.79 | 21.28 |
| **mean** | 0.09 | 126.71 | 30.05 |
| **max** | 0.28 | 250.13 | 169.25 |
|  | **sd** | 0.06 | 44.71 | 33.13 |
| **SPI**  **[sd]** | **min** | 0.08 | -2.52 | 0.03 |
| **median** | 4.14 | -0.08 | 24.39 |
| **mean** | 4.48 | -0.08 | 31.52 |
| **max** | 16.23 | 1.59 | 160.90 |
|  | **sd** | 3.26 | 0.83 | 32.07 |
| **SPEI**  **[sd]** | **min** | 0.29 | -1.19 | 0.05 |
| **median** | 4.23 | -0.15 | 26.71 |
| **mean** | 5.08 | -0.07 | 36.91 |
| **max** | 18.07 | 1.14 | 143.33 |
|  | **sd** | 3.57 | 0.63 | 34.94 |
| **SMI**  **[%]** | **min** | 0.02 | 56.47 | 0.10 |
| **median** | 0.35 | 67.71 | 13.96 |
| **mean** | 0.46 | 68.73 | 31.66 |
| **max** | 1.39 | 92.77 | 92.77 |
|  | **sd** | 0.35 | 7.77 | 33.70 |
| **ESI**  **[sd]** | **min** | 0.42 | -2.02 | 0.00 |
| **median** | 4.13 | -0.32 | 20.23 |
| **mean** | 4.95 | -0.22 | 30.26 |
| **max** | 12.70 | 1.28 | 141.55 |
|  | **sd** | 3.54 | 0.75 | 29.61 |

*Notes:* Cumulative precipitation index (CPI) is measured in unit millimeter [mm], standardized precipitation index (SPI) in standard deviations [sd], standardized precipitation evapotranspiration index (SPEI) in standard deviations[sd], soil moisture index (SMI) in average plant available soil moisture in percentage [%] to maximum plant available soil moisture and evaporative stress index (ESI) in standard deviations [sd]. Statistics only for farms with premium > 0, which is the case for 58 farms with the CPI, 58 farms with the SPI, 53 with the SPEI, 63 for the SMI and 65 for the ESI. Numbers are rounded to two decimal places.

## **S.8 Robustness check with ordinary least squares estimator**

In this section, we derive tick sizes and strike levels with the ordinary least square (OLS) estimator, and display the average changes in risk premiums as well as their significance in Table S13. Using the ordinary least squares (OLS) estimator decreases the risk-reducing potential compared to the quantile regression (QR) estimator. The BEST option with the ordinary least squares estimator (OLS) and assuming moderately risk-averse farmers (=2) is: the evaporative stress index for 30 farms (out of 85), the standardized precipitation index for 11 farms, the standardized precipitation evapotranspiration index for 7 farms, the soil moisture index for 2 farms, the cumulative precipitation index for one farm. 34 farms do not reveal a substantial drought risk for any of the five drought indices and, in terms of expected utility, are no better off by holding a weather index insurance. In Table S14, we show significance levels of differences evaluated with Wilcoxon signed rank tests for the null hypothesis that the risk premiums RPQR are equal to, or larger than, the risk premiums RPOLS. The results show that contract specifics derived with the quantile regression estimator have a significantly greater risk-reducing potential (lower risk premium) than contract specifics derived with the ordinary least square estimator. This is in line with Conradt, Finger and Bokusheva (2015).

**Table S13.**

Absolute (in ‎€/ha) and in parentheses relative (in %) average differences in the risk premium (RP) and their significance for moderately risk-averse (=2) farmers for tick sizes and strike levels derived with the ordinary least square estimator.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
|  |  | **RPn** | | | | | |
|  | **m/n** | **CPI** | **SPI** | **SPEI** | **SMI** | **ESI** | **Uninsured** |
| **RPm** | **CPI** | --- |  |  |  |  | **-0.96\*\*\***  **(-2.52)** |
| **SPI** | **-0.55\*\*\***  **(-1.50)** | --- |  |  |  | **-1.50\*\*\***  **(-3.89)** |
| **SPEI** | -0.13  (-0.44) | 0.42  (1.37) | --- |  |  | **-1.09\*\*\***  **(-2.99)** |
| **SMI** | -0.13  (0.22) | 0.42  (2.07) | 0.00  (1.50) | --- |  | **-1.09\*\*\***  **(-2.54)** |
| **ESI** | **-1.98\*\*\***  **(-4.78)** | **-1.43\*\***  **(-3.31)** | **-1.85\*\*\***  **(-4.17)** | **-1.85\*\*\***  **(-4.84)** | --- | **-2.94\*\*\***  **(-6.89)** |
| **BEST** | **-2.41\*\*\***  **(-6.48)** | **-1.86\*\*\***  **(-5.10)** | **-2.28\*\*\***  **(-5.81)** | **-2.28\*\*\***  **(-6.42)** | **-0.43\*\*\***  **(-1.62)** | **-3.36\*\*\***  **(-8.43)** |

*Notes*:Numbers without brackets display the absolute average reduction in the risk premium (RPm – RPn) in Euros per hectare (€/ha) of winter wheat. Numbers in brackets display the relative average reduction in the risk premium in percentage ((RPm – RPn) / RPn). Numbers are rounded to two decimal places. Asterisks show the Bonferroni-adjusted significance level derived from one-sided paired Wilcoxon signed rank tests: \* at the 1% level, \*\* at the 0.2% level and \*\*\* at the 0.02% level. Null hypotheses tested are RPm ≥ RPn. Significant differences are highlighted in bold. is the coefficient of constant relative risk aversion used in Eq. (8) in the paper, *CPI* the cumulative precipitation index, *SPI* the standardized precipitation index, *SPEI* the standardized precipitation evapotranspiration index, *SMI* the soil moisture index and *ESI* the evaporative stress index.

**Table S14.**

P-values of the one-sided Wilcoxon signed rank tests where we test for differences in the risk premium for contract specifics derived from the quantile regression (QR)- and ordinary least square (OLS) estimator assuming moderately risk-averse farmers ().

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Estimator** |  | **OLS** | | | | | |
|  | **m/n** | **CPI** | **SPI** | **SPEI** | **SMI** | **ESI** | **BEST** |
| **QR** | **CPI** | 2.96E-06 | 4.44E-04 | 2.03E-04 | 1.19E-03 | 2.70E-01 | 6.48E-01 |
| **SPI** | 9.03E-07 | 1.76E-05 | 1.11E-04 | 3.37E-04 | 1.16E-01 | 3.26E-01 |
| **SPEI** | 1.04E-02 | 3.68E-02 | 8.34E-05 | 2.46E-02 | 7.76E-01 | 9.79E-01 |
| **SMI** | 3.55E-06 | 2.16E-04 | 1.23E-04 | 2.37E-08 | 1.21E-01 | 5.58E-01 |
| **ESI** | 6.97E-09 | 1.69E-08 | 5.90E-10 | 2.00E-10 | 8.46E-10 | 4.69E-07 |
| **BEST** | 2.79E-13 | 2.67E-13 | 9.46E-13 | 3.91E-13 | 5.58E-13 | 1.32E-12 |

*Notes:* Null hypotheses tested are RPQR ≥ RPOLS. Tau = 0.3 in the quantile regression and for strike level derivation. is the coefficient of constant relative risk aversion used in Eq. (8) in the paper, *CPI* the cumulative precipitation index, *SPI* the standardized precipitation index, *SPEI* the standardized precipitation evapotranspiration index, *SMI* the soil moisture index and *ESI* the evaporative stress index.

## **S.9 Results for lower partial moments**

Lower partial moments are alternative downside risk measures that do not depend on the assumptions of the expected utility model, i.e. we here do not require to assume farmers to be risk-averse. We derive the lower partial moments () of order j ∈ for farm i and underlying weather index k using Eq. (S8) where we define the threshold c as the 30% quantile from the empirical revenues of farm i without holding a weather index insurance. denotes the probability of falling below the threshold c for the number of realized wealth () observations n of farm i. More specifically, we calculate the lower partial moment of first order () representing the expected shortfall and the lower partial moment of second order () to measure downside variance.

|  |  |
| --- | --- |
|  | (S8) |

**Table S15.**

Composition of the non-uniform insurance product (BEST) for lower partial moments.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **LPMj** | **CPI** | **SPI** | **SPEI** | **SMI** | **ESI** | **Uninsured** |
| **LPM1** | 8 | 10 | 10 | 19 | 31 | 7 |
| **LPM2** | 7 | 10 | 12 | 17 | 32 | 7 |

Notes**:** 85 farms covered. Uninsured means that there is no index causing a lower risk premium than the uninsured status. CPI is the cumulative precipitation index, SPI the standardized precipitation index, SPEI the standardized precipitation evapotranspiration index, SMI the soil moisture index and ESI the evaporative stress index.

Table S15 shows the composition of the non-uniform insurance products that minimize either the expected shortfall (LPM1) or downside variance (LPM2). There is no single best underlying that minimizes the expected shortfall or downside variance. Table S16 shows the absolute and relative average reduction of the expected shortfall and downside variance as well as the significance levels. Table S17 illustrates the corresponding p-values. On average, all five drought indices significantly decrease the expected shortfall and downside variance. In uniform insurance products (where each farm receives the same underlying), the evaporative stress index (ESI) has a significantly lower expected shortfall and downside variance than the other indices with one exception. The expected shortfall of the evaporative stress index is not significantly lower than the expected shortfall of the soil moisture index (SMI). On average, the evaporative stress index decreases the expected shortfall by 23.20% and downside variation by 32.03% compared to being uninsured. The non-uniform insurance product (where each farm receives the most risk-reducing underlying) has a significantly lower expected shortfall and downside variance than all uniform insurance product. On average, the non-uniform insurance product reduces the expected shortfall by 32.42% and downside variance by 44.07% compared to being uninsured. Calculating lower partial moments of higher orders does not change the key finding that tailoring the underlying to each farm has the largest risk-reducing potential (results not shown).

Table S18 shows the number of farms that experience a risk reduction in the expected shortfall and downside variance for each underlying drought index. Table S19 provides summary statistics of the relative risk reductions of each underlying.

**Table S16.**

Absolute (in ‎€/ha) and in parentheses relative (in %) average differences in expected shortfall and downside variance as well as their significance

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
|  |  |  | | | | |  |
|  | **m/n** | **CPI** | **SPI** | **SPEI** | **SMI** | **ESI** | **Uninsured** |
|  | **CPI** | --- |  |  |  |  | **-22.34\*\*\***  **(-15.99)** |
| **SPI** | -1.81  (-1.69) | --- |  |  |  | **-24.14\*\*\***  **(-17.23)** |
| **SPEI** | 1.67  (2.36) | 3.47  (5.06) | --- |  |  | **-20.67\*\*\***  **(-15.49)** |
| **SMI** | -2.63  (-1.77) | -0.82  (0.65) | -4.30  (-2.73) | --- |  | **-24.97\*\*\***  **(-20.00)** |
| **ESI** | **-8.93\*\***  **(-6.60)** | **-7.12\***  **(-4.41)** | **-10.60\*\***  **(-6.97)** | -6.30  (-3.02) | --- | **-31.27\*\*\***  **(-23.21)** |
| **BEST** | **-19.55\*\*\***  **(-18.66)** | **-17.75\*\*\***  **(-16.79)** | **-21.22\*\*\***  **(-19.05)** | **-16.92\*\*\***  **(-14.73)** | **-10.62\*\*\***  **(-10.10)** | **-41.89\*\*\***  **(-32.42)** |
|  | **CPI** | --- |  |  |  |  | **-6’404\*\*\***  **(-20.37)** |
| **SPI** | -552  (-2.82) | --- |  |  |  | **-6’957\*\*\***  **(-22.39)** |
| **SPEI** | 466  (6.92) | 1’019  (14.84) | --- |  |  | **-5’938\*\*\***  **(-19.86)** |
| **SMI** | -1’028  (3.00) | -476  (9.73) | -1'494  (0.74) | --- |  | **-7’432\*\*\***  **(-26.17)** |
| **ESI** | **-3’535\*\***  **(-8.39)** | **-2’983\***  **(-3.43)** | **-4’002\*\***  **(-10.01)** | **- 2’507\*\***  **(-7.02)** | --- | **-9’940\*\*\***  **(-32.03)** |
| **BEST** | **-6’191\*\*\***  **(-28.43)** | **-5’639\*\*\***  **(-25.32)** | **-6’657\*\*\***  **(-28.78)** | **-5’163\*\*\***  **(-24.44)** | **-2’656\*\*\***  **(-14.70)** | **-12’595\*\*\***  **(-44.07)** |

*Notes:* Numbers without brackets display the absolute average reduction for the expected shortfall () and downside variance () in Euros per hectare (€/ha) of winter wheat. Numbers in brackets display the relative average reduction for the expected shortfall () and downside variance () in percentage. Numbers are rounded to two decimal places. Asterisks show the Bonferroni-adjusted significance level derived from one-sided paired Wilcoxon signed rank tests: \* at the 1% level, \*\* at the 0.2% level and \*\*\* at the 0.02% level. Null hypotheses tested are ≥ . Significant differences are highlighted in bold. *CPI* is the cumulative precipitation index, *SPI* the standardized precipitation index, *SPEI* the standardized precipitation evapotranspiration index, *SMI* the soil moisture index and *ESI* the evaporative stress index.

**Table S17.**

P-values of the one-sided Wilcoxon signed rank tests for differences in lower partial moments.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
|  |  |  | | | | |  |
|  | **m/n** | **CPI** | **SPI** | **SPEI** | **SMI** | **ESI** | **Uninsured** |
|  | **CPI** | --- |  |  |  |  | 6.71E-10 |
| **SPI** | 4.56E-01 | --- |  |  |  | 8.75E-10 |
| **SPEI** | 8.55E-01 | 9.57E-01 | --- |  |  | 2.28E-10 |
| **SMI** | 4.77E-02 | 2.05E-01 | 3.89E-02 | --- |  | 3.57E-11 |
| **ESI** | 2.27E-04 | 4.95E-03 | 4.70E-04 | 1.62E-02 | --- | 1.29E-11 |
| **BEST** | 1.24E-13 | 2.67E-13 | 2.67E-13 | 1.23E-11 | 1.24E-09 | 8.58E-15 |
|  | **CPI** | --- |  |  |  |  | 1.37E-09 |
| **SPI** | 2.49E-02 | --- |  |  |  | 8.75E-10 |
| **SPEI** | 7.14E-01 | 9.10E-01 | --- |  |  | 1.15E-09 |
| **SMI** | 1.31E-01 | 3.16E-01 | 5.65E-02 | --- |  | 5.33E-11 |
| **ESI** | 7.83E-04 | 8.44E-03 | 4.11E-04 | 1.76E-03 | --- | 1.98E-11 |
| **BEST** | 8.47E-14 | 2.67E-13 | 5.73E-13 | 5.70E-12 | 1.82E-09 | 8.58E-15 |

Notes: Null hypotheses tested ≥ . CPI is the cumulative precipitation index, SPI the standardized precipitation index, SPEI the standardized precipitation evapotranspiration index, SMI the soil moisture index and ESI the evaporative stress index.

**Table S18.**

Number of farms experiencing a reduction in the risk premium depending on drought index and lower partial moment of first or second order.

|  |  |  |
| --- | --- | --- |
| **Underlying** | **LPM1** | **LPM2** |
| **CPI** | 55 | 52 |
| **SPI** | 55 | 54 |
| **SPEI** | 51 | 50 |
| **SMI** | 57 | 57 |
| **ESI** | 61 | 62 |
| **BEST** | 61 | 62 |

Notes**:** 85 farms covered. CPI is the cumulative precipitation index, SPI the standardized precipitation index, SPEI the standardized precipitation evapotranspiration index, SMI the soil moisture index and ESI the evaporative stress index.

**Table S19.**

Summary statistics of relative (in %) changes in the lower partial moments for each underlying.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **LPM** | **Underlying** | **Min** | **Median** | **Mean** | **Max** | **SD** |
| **LPM1** | **CPI** | -61.00 | -18.60 | -15.99 | 37.57 | 18.81 |
| **SPI** | -63.65 | -18.81 | -17.23 | 46.86 | 20.27 |
| **SPEI** | -66.49 | -16.02 | -15.49 | 42.28 | 18.24 |
| **SMI** | -62.90 | -20.65 | -20.00 | 8.33 | 18.01 |
| **ESI** | -75.78 | -23.27 | -23.21 | 17.05 | 21.23 |
| **BEST** | -75.78 | -31.63 | -32.42 | 0.00 | 17.41 |
| **LPM2** | **CPI** | -82.20 | -19.34 | -20.37 | 83.57 | 26.85 |
| **SPI** | -88.34 | -21.46 | -22.39 | 104.33 | 29.21 |
| **SPEI** | -85.50 | -19.37 | -19.86 | 86.52 | 26.04 |
| **SMI** | -83.13 | -23.72 | -26.17 | 5.34 | 24.34 |
| **ESI** | -90.87 | -26.06 | -32.03 | 24.78 | 29.42 |
| **BEST** | -90.87 | -46.58 | -44.07 | 0.00 | 25.45 |

Notes: Values display the summary statistics for relative changes in the lower partial moments of order j with underlying k compared to the uninsured status in percentages [%] (( – ) / ). Negative values show a reduction in the lower partial moment of order j (i.e. risk exposure). Positive values show an increase in the lower partial moment of order j (i.e. risk exposure). The uninsured status has on average a LPM1 equal to 116.74 Euros per hectare and a LPM2 equal to 25’053Euros per hectare. CPI is the cumulative precipitation index, SPI the standardized precipitation index, SPEI the standardized precipitation evapotranspiration index, SMI the soil moisture index and ESI the evaporative stress index.

## **S.10 Cross-validation**

This section shows the results of a cross-validation to show the sensitivity of our results to potential overfitting. Here, we calibrate insurance contracts (tick size and strike level) for farm i by running pooled quantile regression that leaves-out data of farm i, i.e. we calibrate contracts for each farm i based on the yield-index observations of all the other farms in the sample. Subsequently, we test these contracts on data of the left-out-farm i within the expected utility model and using the farm-individual actuarially fair premium[[4]](#footnote-5).

Table S20 shows summary statistics of the contract specifics. In contrast to contract specifics calibrated on data of farm i as shown in Table S1, all tick sizes in Table S20 reveal a drought risk and the standard deviations of premiums decreases. The average tick size and average strike level is similar between both methods of contract calibration. The composition of the non-uniform insurance product (BEST) is similar to our main results as shown in Table S21.

Table S22 shows the average changes in risk premiums for contracts calibrated by leaving-out farm i and testing these contracts on the left-out-farm i. Table S23 shows the corresponding p-values for one-sided Wilcoxon signed rank tests. The results of this cross-validation confirm the following key-findings of this paper. All of the here applied drought indices have, on average, risk-reducing potential. In uniform insurance (where each farm receives the same underlying), the evaporative stress index (ESI) results, on average, in the largest risk-reducing potential. The non-uniform insurance product (where each farm receives the most risk-reducing underlying, results in much larger risk-reductions than uniform insurance (each farm the same underlying). Each of the here applied indices can result in the largest risk-reducing potential.

Table S24 provides summary statistics of the out-of-sample risk-reductions. Calibrating insurance contracts with pooled quantile regression decreases, on average, the risk-reducing potential of weather index insurance compared to calibrating and evaluating insurance on data of a single farm, which can account for farm-individual drought risks but may be prone to overfitting. Interestingly, the number of farms with the uninsured status as BEST option decreases in this cross-validation and we find, by comparing BEST of the main results (no cross-validation) with BEST of the here presented cross-validation, that 34 out of 85 farms have larger risk-reducing potentials when contracts are calibrated with pooled quantile regression. This indicates that using yield and meteorological data from similar farms for insurance calibration might increase the risk-reducing potential of weather index insurance in some cases.

**Table S20.**

Summary statistics of contract specifics in cross-validation analysis.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Underlying** | **Statistics** | **Tick size**  **[deci-ton / index unit]** | **Strike level**  **[index unit]** | **Premium**  **[Euros / hectare]** |
| **CPI**  **[mm]** | **min** | 0.04 | 121.80 | 0.00 |
| **median** | 0.04 | 125.00 | 12.34 |
| **mean** | 0.04 | 124.80 | 12.31 |
| **max** | 0.05 | 128.10 | 30.23 |
|  | **sd** | 0.00 | 1.47 | 6.03 |
| **SPI**  **[sd]** | **min** | 2.22 | -0.09 | 7.96 |
| **median** | 2.32 | -0.06 | 13.49 |
| **mean** | 2.32 | -0.05 | 13.92 |
| **max** | 2.41 | 0.01 | 24.97 |
|  | **sd** | 0.04 | 0.03 | 3.19 |
| **SPEI**  **[sd]** | **min** | 1.69 | -0.21 | 3.91 |
| **median** | 1.79 | -0.17 | 10.22 |
| **mean** | 1.83 | -0.15 | 10.31 |
| **max** | 2.12 | -0.05 | 16.53 |
|  | **sd** | 0.09 | 0.04 | 2.21 |
| **SMI**  **[%]** | **min** | 0.23 | 68.90 | 2.85 |
| **median** | 0.27 | 69.75 | 16.67 |
| **mean** | 0.28 | 69.72 | 18.73 |
| **max** | 0.33 | 70.38 | 36.71 |
|  | **sd** | 0.02 | 0.33 | 8.93 |
| **ESI**  **[sd]** | **min** | 3.41 | -0.08 | 11.31 |
| **median** | 3.50 | -0.03 | 23.45 |
| **mean** | 3.52 | -0.04 | 23.63 |
| **max** | 3.63 | 0.00 | 28.87 |
|  | **sd** | 0.06 | 0.02 | 2.84 |

*Notes:* Cumulative precipitation index (CPI) is measured in millimeter [mm], standardized precipitation index (SPI) in standard deviations [sd], standardized precipitation evapotranspiration index (SPEI) in standard deviations[sd], soil moisture index (SMI) in average plant available soil moisture in percentage [%] to maximum plant available soil moisture and evaporative stress index (ESI) in standard deviations [sd]. 30% quantile used in quantile regression.

**Table S21.**

Composition of the non-uniform insurance (BEST) for the cross-validation analysis assuming moderately risk-averse ( =2) farmers.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **CPI** | **SPI** | **SPEI** | **SMI** | **ESI** | **Uninsured** |
| 4 | 12 | 5 | 9 | 48 | 7 |

Notes: is the coefficient of constant relative risk aversion used in Eq. (8) in the paper, CPI the cumulative precipitation index, SPI the standardized precipitation index, SPEI the standardized precipitation evapotranspiration index, SMI the soil moisture index and ESI the evaporative stress index.

**Table S22.**

Absolute (in ‎€/ha) and in parentheses relative (in %) average differences in the risk premium (RP) and their significance for moderately risk-averse farmers ( =2) for the cross-validation analysis.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
|  |  | **RPn** | | | | | |
|  | **m/n** | **CPI** | **SPI** | **SPEI** | **SMI** | **ESI** | **Uninsured** |
| **RPm** | **CPI** | --- |  |  |  |  | **-1.36\*\*\***  **(-4.24)** |
| **SPI** | -0.06  (-0.41) | --- |  |  |  | **-1.42\*\*\***  **(-4.60)** |
| **SPEI** | 0.62  (2.13) | 0.68  (2.67) | --- |  |  | **-0.74\*\*\***  **(-2.29)** |
| **SMI** | **-0.49\***  **(-0.94)** | -0.42  (-0.39) | **-1.10\*\*\***  **(-2.90)** | --- |  | **-1.85\*\*\***  **(-5.71)** |
| **ESI** | **-1.63\*\***  **(-4.19)** | **-1.57\*\*\***  **(-3.73)** | **-2.25\*\*\***  **(-6.06)** | **-1.14\*\*\***  **(-3.20)** | --- | **-2.99\*\*\***  **(-8.43)** |
| **BEST** | **-2.38\*\*\***  **(-8.45)** | **-2.32\*\*\***  **(-7.97)** | **-3.00\*\*\***  **(-10.30)** | **-1.89\*\*\***  **(-6.94)** | **-0.75\*\*\***  **(-3.57)** | **-3.74\*\*\***  **(-12.32)** |

*Notes*:Numbers without brackets display the absolute average reduction in the risk premium (RPm – RPn) in Euros per hectare (€/ha) of winter wheat. Numbers in brackets display the relative average reduction in the risk premium in percentage ((RPm – RPn) / RPn). Numbers are rounded to two decimal places. Asterisks show the Bonferroni-adjusted significance level derived from one-sided paired Wilcoxon signed rank tests: \* at the 1% level, \*\* at the 0.2% level and \*\*\* at the 0.02% level. Null hypotheses tested are RPm ≥ RPn. Significant differences are highlighted in bold. is the coefficient of constant relative risk aversion used in Eq. (8) in the paper, *CPI* the cumulative precipitation index, *SPI* the standardized precipitation index, *SPEI* the standardized precipitation evapotranspiration index, *SMI* the soil moisture index and *ESI* the evaporative stress index.

**Table S23.**

P-values of one-sided Wilcoxon signed rank tests for differences in the risk premium for the cross-validation analysis assuming moderately risk-averse farmers (=2).

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
|  |  | **RPn** | | | | | |
|  | **m/n** | **CPI** | **SPI** | **SPEI** | **SMI** | **ESI** | **Uninsured** |
| **RPm** | **CPI** | --- |  |  |  |  | 2.21E-08 |
| **SPI** | 5.94E-02 | --- |  |  |  | 4.82E-07 |
| **SPEI** | 9.99E-01 | 1.00E+00 | --- |  |  | 1.78E-04 |
| **SMI** | 7.33E-03 | 5.06-E02 | 3.84E-06 | --- |  | 3.71E-08 |
| **ESI** | 4.09E-04 | 1.22E-05 | 2.21E-08 | 1.57E-05 | --- | 4.73E-08 |
| **BEST** | 4.00 E-15 | 5.78E-14 | 4.00E-15 | 1.84E-14 | 5.94E-08 | 8.58E-15 |

*Notes:* Null hypotheses tested are RPm ≥ RPn. Tau = 0.3 in the quantile regression and for strike level derivation. is the coefficient of constant relative risk aversion used in Eq. (8) in the paper, *CPI* the cumulative precipitation index, *SPI* the standardized precipitation index, *SPEI* the standardized precipitation evapotranspiration index, *SMI* the soil moisture index and *ESI* the evaporative stress index.

**Table S24.**

Summary statistics of relative changes in the risk premiums for cross-validation analysis compared to being uninsured and in percentages [%] for moderately risk-averse farmers (=2).

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Underlying** | **Min** | **Median** | **Mean** | **Max** | **SD** |
| **CPI** | -17.84 | -4.47 | -4.24 | 16.62 | 6.15 |
| **SPI** | -19.82 | -6.18 | -4.60 | 15.66 | 7.83 |
| **SPEI** | -12.80 | -1.92 | -2.29 | 19.81 | 5.83 |
| **SMI** | -24.40 | -7.32 | -5.71 | 12.96 | 10.52 |
| **ESI** | -36.38 | -10.69 | -8.43 | 27.86 | 13.10 |
| **BEST** | -36.38 | -11.94 | -12.32 | 0.00 | 8.34 |

*Notes:* is the coefficient of constant relative risk aversion used in Eq. (8) in the paper, *CPI* the cumulative precipitation index, *SPI* the standardized precipitation index, *SPEI* the standardized precipitation evapotranspiration index, *SMI* the soil moisture index and *ESI* the evaporative stress index.

## **S.11 References**

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1. This distribution is recommended in Vicente-Serrano et al. (2010). [↑](#footnote-ref-2)
2. Note that the average risk premium in our sample is 2.6% of the expected generated wealth. If weather index insurance would completely remove all risks, i.e. make wheat production completely risk-free, the average increase in the certainty equivalent would be 2.6%. Loading the actuarially fair premium reduces the maximum increase in the certainty equivalent because the expected generated wealth is lowered. [↑](#footnote-ref-3)
3. A loading above 20% increases the number of farms that are no better off with weather index insurance. The loading factors presented above are in line with previous publications (e.g. Dalhaus, Musshoff and Finger, 2018; Kellner and Musshoff, 2011; Leblois et al., 2014; Shen and Odening, 2013). The results show the need for a cost-efficient insurance supply, which is particularly feasible with weather index insurance. [↑](#footnote-ref-4)
4. We use pooled quantile regression because the length of our time series limits a split of farm-individual data into a calibration and testing set. See Conradt, Finger and Bokusheva (2015) who split farm-individual data into a calibration and testing set for a case study with 30 years of data. [↑](#footnote-ref-5)