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Final report on the design of whether-indexed and catastrophe insurances

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1. Research activities

The use of insurance tools to cope with extreme and catastrophic events is more and more debated (Bucheli, Dalhaus and Finger 2021), due to the increasing amount of available data on weather conditions and the higher frequency of natural disasters. The research activities developed feasibility studies for indexed insurance and catastrophe insurance focusing on crops that seem more suited for these instruments: wheat (for indexed insurance) and crops covered by Agri-CAT Fund (i.e., almond, apple, apricot, corn, durum wheat, grape wine, kiwi, orange, peach, pear, tomato) for catastrophe insurance.

The index-based insurance allows covering territories and crops for which the information base is quite scarce because farm-level data is difficult to collect and monitor. The feasibility has been investigated through regression models, fed by data on agronomic performance (yields) and on climate dynamics (Conradt, Finger and Bokusheva 2015). These models can highlight which indexes, and trigger mechanisms, may be successfully adopted by insurance companies.

The catastrophe insurance is potentially relevant because it allows to cover extreme events (i.e., systemic in nature and with an impact of high magnitude) that, being more and more frequent, are a threat for the entire agri-food sector. Quantile regressions explore the dynamics of the tails and thus allow us to investigate how rare events are connected with less frequent yield realizations: this information allows to model insurance contracts to cope with catastrophic events.

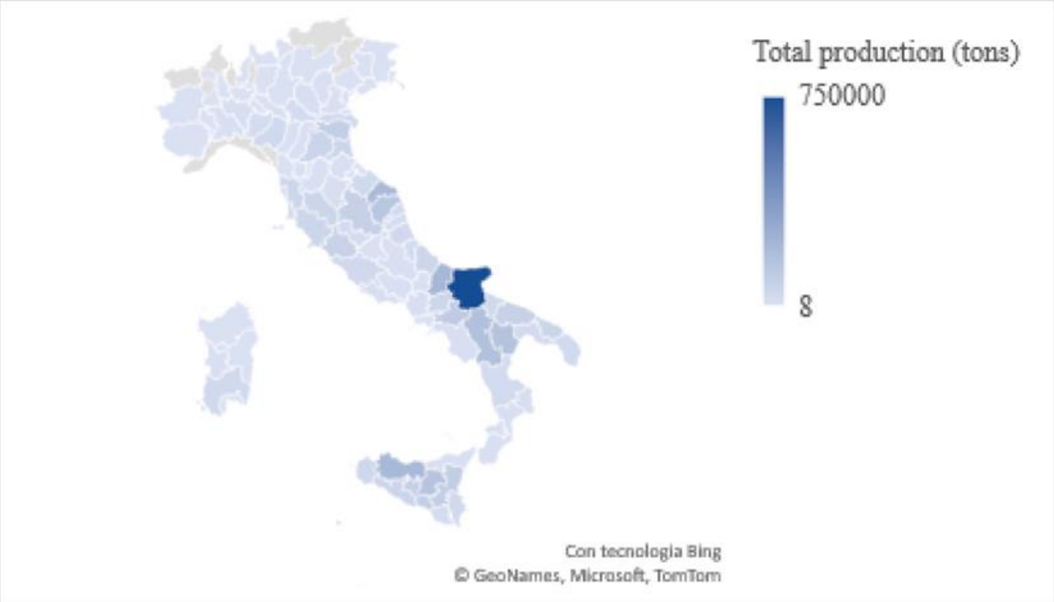
1.1. Outcomes

1.1.1. Index-based insurance

The research activities focused on the relationship between weather variables and yield of durum wheat. The evidence provided allowed to assess the feasibility of a weather index insurance.

Durum wheat is the main cereal crop in Italy with a production of 4 million of tons cultivated in 1.2 million of hectares. Production is concentrated in Southern and Central Italy, while Northern Italy produces slightly more than 10 percent of national production. Province of Foggia (Southern Italy) is the main durum wheat producer of Italy with 750,000 tons (see figure 1).

Figure 1. Durum wheat Italian production by province Source: ISTAT, 2020.



Source: Tappi et al. (2023a).

The durum wheat crop is more susceptible to specific weather events in certain phenological stages, more specifically, cold sensitivity is higher during the starting and development stages, in which temperatures of 0 °C may cause growth arrests and considerable damages, especially when the soil is moist (Baldoni and Giardini, 2000; Angelini, 2007). Tack et al., 2015, found that freezing temperature in the fall season is one of the biggest drivers of wheat yield losses until 9 percent. Although many cultivars have high levels of frost tolerance, cold stress (<0 °C) during the vegetative stage may lead to a reduction in the rate of photosynthesis or even leaf, root, and plant death, also threatening seedling survival (Whaley et al., 2004; Barlow et al., 2015). Moreover, the flowering stage is susceptible to frost (Baldoni and Giardini, 2000). Heat and drought occurring in the flowering and grain-filling stages (i.e., maturity-end) may lead leaf senescence, pollen sterility, oxidative damages, reduction in photosynthesis, adversely affecting the yields (Farooq et al., 2014; Rezaei et al., 2015; Zampieri et al., 2017). High temperatures during Spring season (>34 °C) concomitant with flowering and grain filling stages may reduce yields until 7.6 percent (Tack et al., 2015). Moreover, higher temperatures increase the evapotranspiration demand, reduces the crop water use efficiency, causes water stress or its scarcity, and is highly related to yield losses (Saadi et al., 2015; Zampieri et al., 2017). Additionally, heavy rainfall may cause significant production losses due to the proliferation of pathogens, nutrient leaching, soil erosion, inhibition of oxygen uptake by roots (i.e., hypoxia or anoxia), waterlogging, and lodging (Zampieri et al., 2017). However, rainfall in the Spring may partially offset negative warming effects on yields (Tack et al., 2015).

We identified five phenological stages of durum wheat: (i) starting, from sowing to leaf development; (ii) development, from leaf development to anthesis; (iii) flowering, from anthesis to seed fill; (iv) maturity, from seed fill to dough stage; (v) end, maturity complete. Each phase has been identified through two approaches: (a) fixed time windows provided by Baldoni and Giardini, 2000, and Angelini, 2007, which indicated the time-period of crop phenology (table 1); (b) GDD, i.e., the summatory of mean daily temperatures starting from sowing dates (table 2). This is computed by assigning a heat value to each day, giving an estimate of the amount of seasonal growth of plants, and is commonly used to predict events and schedule management activities (Miller et al., 2001).

Table 1. Phenological stages of durum wheat identified by fixed time windows.

Stage	BGA (Macro-region)	FAO 56
Starting	2nd – 3rd decade of October (Northern Italy) 1st – 2nd decade of November (Center of Italy) 2nd – 3rd decade of November (Southern Italy and Islands)	November 15 – December 14
Development	2nd – 3rd decade of March – by the end of April	December 15 – May 03
Flowering	2nd – 3rd decade of May	May 04 – May 14
Maturity	3rd decade of May – by the end of June	May 15 – June 12
End	3rd decade of June – 1st decade of July	June 13 – July 12

Source: Tappi et al. (2023a).
Note: BGA identifies phenological stages provided by Baldoni and Giardini (2000), and Angelini (2007). Flowering stage has been identified in FAO 56 as the first 10 days of maturity stage (Angelini, 2007).

Table 2. Durum wheat varieties and phenological stages identified by GDD ranges.

Stage	Growing Degree Days (◦C)		
	Early varieties	Middle varieties	Late varieties
Starting	0–169	0–189	0–208
Development	169–807	189–854	208–901
Flowering	807–1068	854–1121	901–1174
Maturity	1068–1434	1121–1495	1174–1556
End	1434–1538	1495–1602	1556–1665

Source: Tappi et al. (2023a).
Notes. GDD 15/25/Agri4Cast identifies the sowing dates for the calculation of Growing Degree Days: November 15 (GDD 15); November 25 (GDD 25); sowing dates provided by Agri4Cast dataset.

For GDD calculation, we considered the following sowing dates: November 15 (Allen et al., 1998), November 25 (10-days shift)10, and sowing dates of wheat provided by EU JRC Agri4Cast dataset for each province investigated, therefore, GDD 15/25/EU will identify the sowing dates for the calculation of GDD. Furthermore, we included three durum wheat varieties (i.e., early, middle, and late) based on GDD centigrade ranges to assess the responsiveness of varieties to change in weather in specific phenological stages (see table 2).

There are several approaches to calculating phenological stages (see tables A.1-A.2).

1.1.2. Catastrophe insurance

The research activities focused on the relationship between catastrophic weather events and demand of subsidised crop insurance, which covers also catastrophic events. We study this relationship within the Italian risk management framework, a relevant case study in terms of weather risk exposure (e.g., Tappi et al., 2023), insurance market structures (e.g., Coletta et al., 2018), and political interventions (e.g., Santeramo, Russo, and Lamonaca, 2023). The evidence provided allowed to assess the feasibility of a catastrophe insurance.

The analysis considers all the Italian provinces and eleven crops covered by Agri-CAT Fund (i.e., almond, apple, apricot, corn, durum wheat, grape wine, kiwi, orange, peach, pear, tomato), observed over the period between 2010 and 2020. The variables indicating the occurrence of extreme weather events are built using province-specific daily weather data (i.e., precipitation in mm for flood; 3-months average minimum and maximum temperatures in °C and cumulated precipitation in mm for drought; minimum temperature in °C for frost), collected from the JRC MARS Meteorological Database. To ensure comparability between different sources of data, the obtained weather variables are aggregated at the annual level. To understand the potential correlation between the occurrence of extreme weather events and the insurance demand, we collected province- and crop-specific annual data on insured value (in EUR) and insurance premium (in EUR) from the 'Istituto di Servizi per il Mercato Agricolo Alimentare' (ISMEA). From the same source we gathered annual data on prices of crops at the national level. This information, combined with data province-specific annual data on crop production (in t) from the 'Istituto Nazionale di Statistica' (ISTAT), allowed us to build a proxy of the gross saleable production. By comparing the insured value and the gross saleable production, we obtained the share of insured value over the value of production, that is the insurance demand metric used in this analysis.

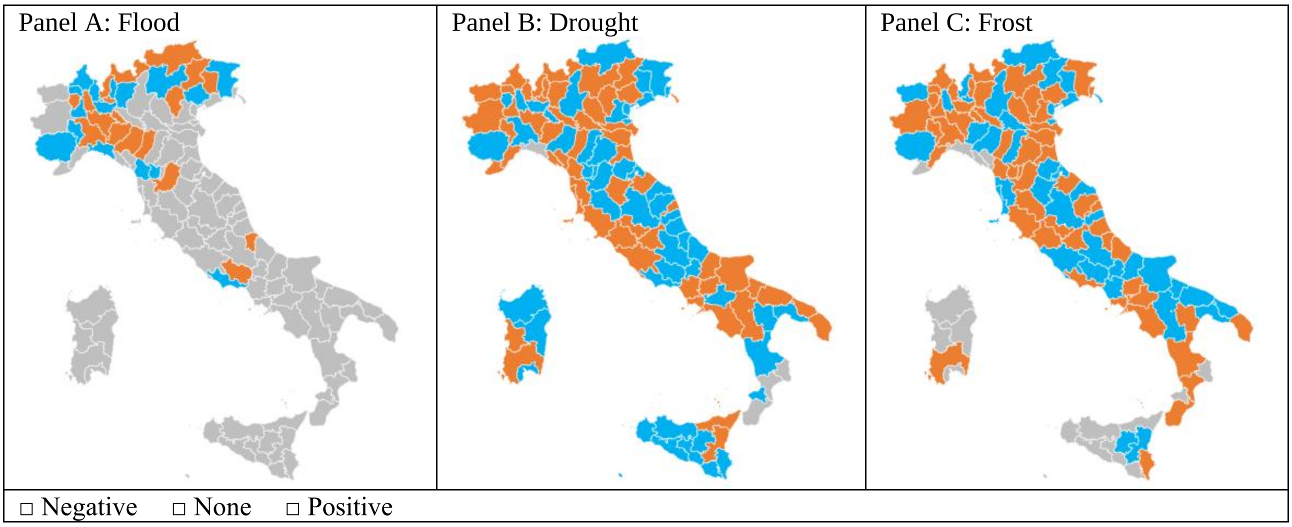
The descriptive statistics of the main variables in 2010 (start year of the sample) and 2020 (end year of the sample) are in table 3. Details are provided by geographical area and type of crop. The share of insured value per value of production tripled in a decade, from 0.46 in 2010 to 1.64 in 2020. This increase is mostly to be attributed to an increase in the share of insured value in Northern areas and of spring-summer crops. The increase in the share of insured value is accompanied by a reduction both in insurance premiums (from 0.33 to 0.20 million EUR in 2010-2020) and crop yields (from 16.47 to 15.57 t/ha in 2010-2020). In a decade, the incidence of flood (non-existent in 2010) and of drought events has increased and the occurrence of frost events has reduced. The occurrence of extreme weather events is heterogeneous across Italy: for instance, flood and frost events are more frequent in Northern area whereas drought events are more common in Southern area. Their incidence is also related to the type of crops cultivated in these areas: for instance, drought events hit more frequently autumn-winter crops, that are almond and apricot, highly spread in Southern area. The correlation between the share of insured value per value of production and the occurrence of extreme weather events is, as a consequence, heterogeneous across geographical areas (figure 2).

Table 3. Descriptive statistics of main variables in 2010 and 2020, details by geographical area and crop dimensions.

	Insured value/value of production		Premium (Million EUR)		Yield (t/ha)		Flood (%)		Drought (%)		Frost (%)	
	2010	2020	2010	2020	2010	2020	2010	2020	2010	2020	2010	2020
All	0.46 (±0.90)	1.64 (±4.38)	0.33 (±2.35)	0.20 (±0.92)	16.47 (±14.58)	15.57 (±15.36)	0.00 (±0.00)	0.06 (±2.53)	2.49 (±15.60)	5.70 (±23.19)	10.81 (±31.05)	6.63 (±24.89)
North	0.51 (±0.92)	2.69 (±6.01)	0.71 (±0.35)	0.40 (±0.14)	18.65 (±14.68)	13.08 (±11.69)	0.00 (±0.00)	0.08 (±2.83)	0.00 (±0.00)	2.95 (±16.92)	20.27 (±40.21)	14.02 (±34.72)
South	0.42 (±0.87)	0.72 (±1.63)	0.38 (±0.18)	0.47 (±0.26)	14.83 (±14.29)	17.57 (±17.52)	0.00 (±0.00)	0.05 (±2.27)	4.37 (±20.44)	7.77 (±26.78)	3.70 (±18.88)	1.08 (±10.33)
Autumn-winter crop	0.42 (±0.84)	0.48 (±0.40)	0.01 (±0.02)	0.03 (±0.07)	9.98 (±4.38)	6.55 (±5.83)	0.00 (±0.00)	0.06 (±2.43)	1.69 (±12.88)	6.27 (±24.24)	9.37 (±29.14)	9.94 (±29.93)
Spring-summer crop	0.47 (±0.91)	1.69 (±4.48)	0.40 (±2.59)	0.21 (±0.96)	17.88 (±15.61)	16.43 (±15.71)	0.00 (±0.00)	0.06 (±2.54)	2.67 (±16.13)	5.65 (±23.09)	11.12 (±31.44)	6.33 (±24.36)

Notes: Descriptive statistics are mean and, in parentheses, standard deviation. The North includes North-West (i.e., Valle d'Aosta, Liguria, Lombardia, and Piemonte regions) and North-East (i.e., Trentino-Alto Adige, Veneto, Friuli-Venezia Giulia, and Emilia-Romagna regions) of Italy. The South considers Centre (i.e., Toscana, Umbria, Marche, and Lazio regions), South (i.e., Abruzzo, Molise, Campania, Puglia, Basilicata, and Calabria regions), and Islands (i.e., Sicilia and Sardegna regions) of Italy. Autumn-winter crops include almond and apricot. Spring-summer crops include apple, corn, durum wheat, grape wine, kiwi, orange, peach, pear, tomato.

Figure 2. Correlation between the share of insured value per value of production and extreme weather events.



1.2. Applications and impacts

1.2.1. The weather-yield relationship

The research activities examined the relationship between durum wheat yields and weather variables in Italy. The econometric model includes three temporal and design specifications (table 4). In specification A, yields are determined by the squares of temperature, precipitation, and crop evapotranspiration. In specification B, yields are linked to temperature, precipitation, and crop water deficit. In specification C, it includes the squares of precipitation, evapotranspiration, water deficit, and daily temperature range. To capture nonlinearity, the squares of the weather variables are included. Fixed effects are included in all specifications to account for unobservable factors like soil quality or management practices across time and space (Tack et al., 2015; Kolstad and Moore, 2020). Low temperatures are found to negatively impact yields up to 19°C, while high temperatures have a positive effect until around 39°C. This underscores a significant correlation between weather conditions and durum wheat productivity, with low temperatures generally detrimental and high temperatures beneficial in a nonlinear manner. The incorporation of temporal and design-specific variables, such as evapotranspiration (ETc), cumulative water deficit (CWD), and diurnal temperature range (DTR), does not alter the observed negative relationship between low temperatures and yields or the positive association between ETc and yields. However, the observed positive effects of high temperatures and negative effects of precipitation are more contingent on the model design, as these are evident only in specific specifications such as FAO 56 (B) and GDD EU (B and C).

Table 4. Relationship among durum wheat yields and weather conditions using different temporal and design specifications.

	BGA			FAO 56		GDD 15		GDD 25		GDD EU	
	A	B	C	B	C	B	C	B	C	B	C
T min	-0.07926***	-0.05365**		-0.07592***		-0.05392***		-0.04081**		-0.05372***	
	(0.01058)	(0.02432)		(0.01202)		(0.01595)		(0.01602)		(0.01804)	
$(\text{T min})^2$	0.00215***	0.00133		0.00219***		0.00021		-0.00101		0.00052	
	(0.00044)	(0.00101)		(0.00062)		(0.00116)		(0.00115)		(0.00137)	
T max	0.05854***	0.02770		0.03399**		0.02017		-0.01226		-0.00448	
	(0.01243)	(0.02962)		(0.01491)		(0.02326)		(0.02248)		(0.02609)	
$(\text{T max})^2$	-0.00077**	0.00013		0.00025		0.00111		0.00236***		0.00231**	
	(0.00030)	(0.00069)		(0.00042)		(0.00082)		(0.00077)		(0.00093)	
DTR			0.01593		0.03735***		0.04951***		0.04290***		0.03904***
			(0.01376)		(0.00887)		(0.01127)		(0.01139)		(0.01315)
DTR^2			0.00044*		0.00012		0.00004		0.00042		0.00069
			(0.00026)		(0.00021)		(0.00038)		(0.00037)		(0.00044)
(Prec)	-0.00085	-0.00612	-0.00780	-0.00502	-0.00936	-0.00411	-0.00557	-0.00983	-0.01178	-0.02373*	-0.02580**
	(0.00633)	(0.01217)	(0.01213)	(0.00829)	(0.00825)	(0.01085)	(0.01081)	(0.01015)	(0.01013)	(0.01250)	(0.01244)
$(\text{Prec})^2$	-0.00004	-0.00039	-0.00034	-0.00020	-0.00010	-0.00008	-0.00007	0.00003	0.00006	0.00039	0.00041
	(0.00022)	(0.00044)	(0.00044)	(0.00031)	(0.00031)	(0.00035)	(0.00035)	(0.00038)	(0.00038)	(0.00040)	(0.00039)
ETc		0.05072***	0.04162***	0.07332***	0.04434***	0.12368***	0.11906***	0.12728***	0.12684***	0.16193***	0.14932***
		(0.01396)	(0.01304)	(0.01312)	(0.01165)	(0.02567)	(0.02528)	(0.02500)	(0.02434)	(0.03137)	(0.03073)
CWD		-0.00282	-0.00284	-0.00113	-0.00166	0.00020	-0.00062	-0.00106	-0.00152	0.00168	0.00058
		(0.00248)	(0.00247)	(0.00238)	(0.00237)	(0.00573)	(0.00570)	(0.00248)	(0.00248)	(0.00616)	(0.00613)
Obs.	162,909	54,472	54,472	107,159	107,159	68,299	68,299	67,271	67,271	54,300	54,300

Source: Tappi et al. (2023a).

Notes: temperatures are not shown in the specification C due to the collinearity with daily range temperature variable which seems to have a positive effect on yields. We also provided an assessment of quality of estimation through R2 measurement. The inclusion of variables is slightly increasing the R2, in other terms, the R2 of the restricted specifications never exceed the R2 of unrestricted.

Focusing on durum wheat in Italy, we investigate how weather events that occur in phenological stages identified by different approaches (i.e., temporal specifications) and how different weather variables and combination of thereof (i.e., design specifications) of the econometric model may lead to different results in the yield-weather assessment.

We found several connections among weather and yields. The choice of sowing dates may play a crucial role: a 10-days shift, using the same temporal and design approaches, may lead to a different estimation of yield losses due to changes in weather. Clustering for spatial dummies among provinces, it emerged that some weather variables are more important in some provinces than others. This should be considered by policymakers to plan risk management tools as weather insurances based on indexes which may be different depending on the location. Another implication is that the choice of specifications of the econometric model is very important to catch the relationships weather-yields. The negative effect of low temperatures, especially during the early stages, is always caught, regardless of specifications. GDD EU provided by Agri4Cast dataset seems to be the best model that is likely closest to what could happen on farms supported by the agronomic literature: minimum temperatures negatively affect the yields when they occur in the starting and development stages, maximum temperatures negatively affect the yields when they occur in the flowering stage, heavily precipitation negatively affect the yields when it occurs in the maturity stage. Changes in design and temporal specifications seem to have no effect on the negative relationship low temperatures-yields and on the positive relationship -yields. This result may contribute to establish a triggering index (i.e., for minimum temperatures) that represent a main challenge for agricultural policy focused on agricultural risk management.

1.2.2. The weather-insurance relationship

The research activities examined the relationship between the co-occurrence of catastrophic weather events and the level of subsidised crop insurance. Table 5 shows the Ordinary Least Square (OLS) estimates, not including (column 1) and including (column 2) extreme weather events, respectively. The estimates indicate that the share of insured value per value of production exhibits a positive correlation with premium and a negative correlation with yield. The insurance demand is expected to increase by 5.6 percent with a 10 percent increase in premium and to decrease by 9.8 percent with a 10 percent increase in yield. The positive own-price elasticity of insurance demand is indicative of the prevalence of the insurance demand in a risky environment, consolidating the arguments, for instance, of (Miranda, 1991; Goodwin, 1993; Goodwin, 1994; Makki and Somwaru, 2001), who conclude that high-risk participants tend to dominate the insurance market. Also, the results corroborate the recent findings of (Turner and Tsiboe, 2022), indicating that the insurance demand is relatively more correlated (in absolute terms) to changes in yield than in premium.

Focusing on the interpretation of estimates in column (2), we find a positive correlation between the share of insured value per value of production and the occurrence of flood and frost events. The estimated semi-elasticities suggest that the insurance demand is relatively more correlated to the incidence of flood than of frost events.

The demand for crop insurance increase from 0.9 percent to 1.8 percent in response to the occurrence of extreme weather events. These figures are obtained by exponentiating the value of constant in the baseline specification (column 1) and the value of constant increased by the values estimated for extreme weather events (column 2).

Table 5. Drivers of insurance demand.

	(1)	(2)
Variables	Baseline	Under extreme weather events
Premium	0.5651***	0.5636***
	(0.0249)	(0.0249)
Yield	-0.9818***	-0.9821***
	(0.1235)	(0.1229)
Flood		0.3772**
		(0.1595)
Drought		0.0341
		(0.0683)
Frost		0.3093***
		(0.0549)
Constant	-4.7213***	-4.7309***
	(0.3332)	(0.3312)
Dep. var.	Share of insured value	Share of insured value
Fixed effects	Crop	Crop
Observations	283,167	283,167
R-squared	0.68	0.68

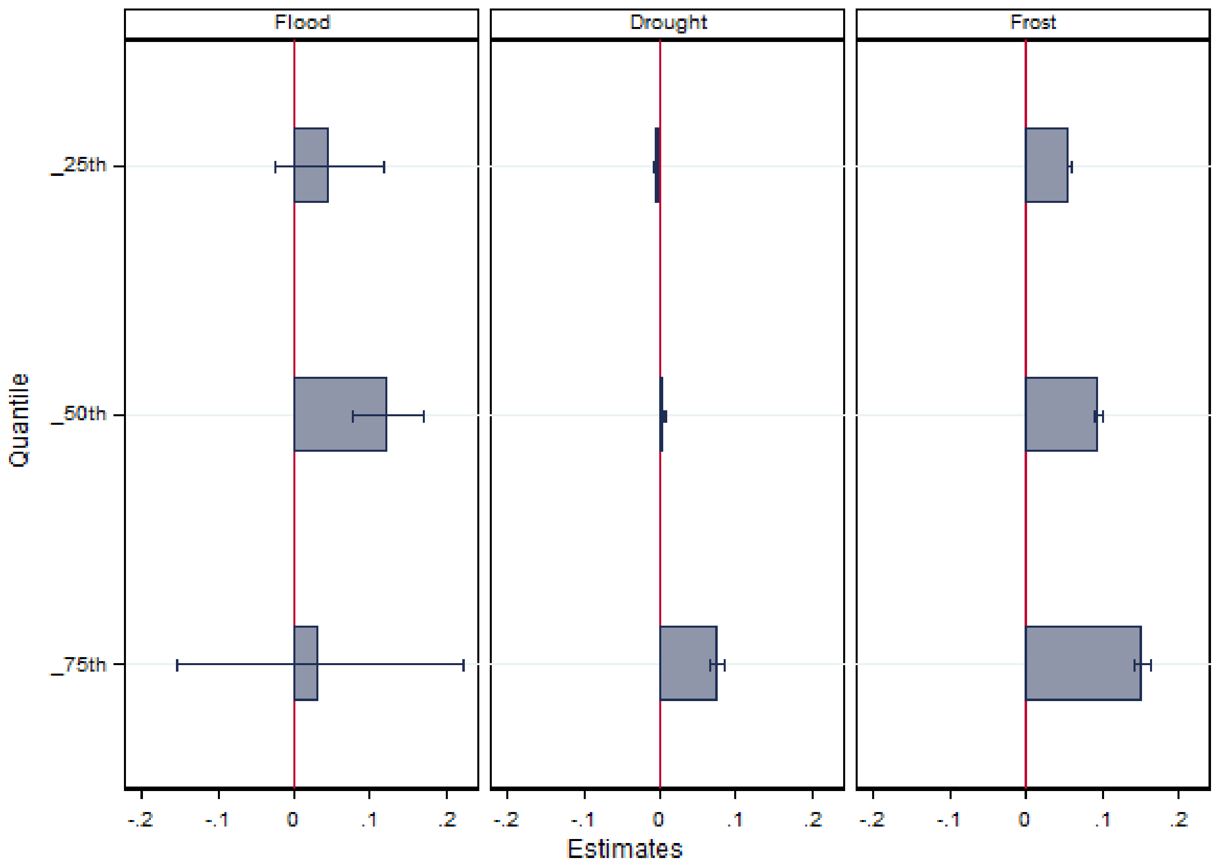
Notes: Ordinary Least Square estimates. The dependent variable is the natural logarithm of the share of insured value over the value of production. All specifications include the natural logarithm of yield and premium, crop-specific fixed effects, and a constant. The specification under extreme weather events includes dummy variables proxying the occurrence of flood, drought, and frost. Standard errors, clustered at province-crop level, are in parentheses. *** Significant at the 1 percent level. ** Significant at the 5 percent level. * Significant at the 10 percent level.

The share of insured value of production is highly heterogenous across crop-by-province combinations and tends to be concentrated in 25 percent of the sample. The heterogeneity in concentrations of the insurance uptake reflects the structure of the Italian insurance market, characterised by the presence of a limited number of provinces –especially those in the North of Italy– and crops –generally the most valuable ones such as wine grapes– (e.g., ISMEA, 2020). The increase in the share of insurance uptake overtime is basically associated with a growth in the insured values in the North and for most valuable crops.

Yu et al. (2021) suggest using a quantile regression approach to capture differential relationships across crop-by-province combinations characterised by different shares of insurance coverage. Figure

3 presents the distributions of the estimated coefficients (and related confidence intervals) of CAT events by quantile.

Figure 3. Differential relationship between CAT events and insurance uptake.



Notes: Bars represent the magnitude of quantile regression estimates and capped spikes are the 95 percent confidence intervals of the coefficients for each quantile equation. The dependent variable is the share of insured value of production. All specifications include the natural logarithm of yield and premium, crop-specific fixed effects, a constant (omitted in the figure), and dummy variables proxying the occurrence of flood, drought, and frost events. The variable 'flood' is significant only at the 50th percentile. The variable 'drought' is not significant at the 50th percentile. Standard errors are clustered at province-crop level.

The positive association between the insurance uptake and frost events is confirmed. We also detect a significant increase in the insured uptake associated with an increasing occurrence of drought events. The estimated semi-elasticities suggest that the insurance demand is relatively more responsive to the incidence of frost than of drought events. The coefficient estimates range from -0.0057 to 0.0757 for drought and between 0.0565 and 0.1538 for frost. The difference of estimated coefficients across quantiles indicates that there is an increasingly positive effect for higher quantiles as compared to lower ones. This suggests that crop-by-province combinations with larger shares of insurance tend to be increasingly responsive to the occurrence of drought and frost events.

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2. Research outputs

2.1. Articles published in peer-reviewed journals

1. Santeramo, F. G., & Maccarone, I. (2022). Historical crop yields and climate variability: analysis of Italian cereal data. *Italian Review of Agricultural Economics*, *77*(2), 77-91. DOI: 10.36253/rea-13596 [Scopus: Q2] (link).
2. Santeramo, F. G., Russo, I., & Lamonaca, E. (2022). Italian subsidised crop insurance: what the role of policy changes. *Q Open*, qoac031. DOI: 10.1093/qopen/qoac031 [Scopus: Q2] (link).
3. Tappi, M., Nardone, G., & Santeramo, F. G. (2022). On the relationships among durum wheat yields and weather conditions: evidence from Apulia region, Southern Italy. *Bio-based and Applied Economics*, *11*(2), 123-130. DOI: 10.36253/bae-12160 [Scopus: Q2] (link).
4. Tappi, M., & Santeramo, F. G. (2022, November). (Extreme) Weather index-based insurances: data, models, and other aspects we need to think about. In *2022 IEEE Workshop on Metrology for Agriculture and Forestry (MetroAgriFor)* (pp. 313-317). IEEE. DOI: 10.1109/MetroAgriFor55389.2022.9964979 [Scopus] (link).
5. Tappi, M., Carucci, F., Gagliardi, A., Gatta, G., Giuliani, M. M., & Santeramo, F. G. (2023). Earliness, phenological phases and yield-temperature relationships: evidence from durum wheat in Italy. *Bio-based and Applied Economics*, 12(2), 115-125. DOI: 10.36253/bae-13745. [Scopus: Q2] (link).
6. Tappi, M., Carucci, F., Gatta, G., Giuliani, M. M., Lamonaca, E., & Santeramo, F. G. (2023). Temporal and design approaches and yield-weather relationships. *Climate Risk Management*, 40, 100522. DOI: 10.1016/j.crm.2023.100522 [Scopus: Q1] (link).

2.2. Articles published in outreach journals

1. Santeramo, F. G., Russo, I., & Lamonaca, E. (2022). L’assicurazione agricola agevolata in Italia: il ruolo delle riforme. *Agrarpolitik*, 19/12/2022 (link).

2.3. Presentation at international and national conferences

1. Tappi, M., Carucci, F., Gagliardi, A., Gatta, G., Giuliani, M.M., Lamonaca, E., Santeramo, F.G. (2022). Temporal and design approaches to catch further yield-weather relationships: evidence on durum wheat in Italy. In *11th AIEAA Conference - CAP, Farm to Fork and Green Deal: policy coherence, governance, and future challenges*, 16-17 June 2022, Viterbo (Italy).
2. Tappi, M., & Santeramo, F. G. (2022, November). (Extreme) Weather index-based insurances: data, models, and other aspects we need to think about. In *2022 IEEE Workshop on Metrology for Agriculture and Forestry*, 3-5 November 2022, Perugia (Italy).

A. Appendix

A.1. Other approaches to obtain phenological stages.

Table A.1. Dates of occurrence and GDD values of durum wheat among phenological stages.

	starting		growing		anthesis		maturity		end	
	start	end	start	end	start	end	start	end	start	end
Early-maturing	Nov, 15	Dec, 1	Dec, 2	Mar, 29	Mar, 30	Apr, 19	Apr, 20	May, 16	May, 17	May, 22
(GDD)	(0)	(168)	(169)	(806)	(807)	(1067)	(1068)	(1433)	(1434)	(1538)
Middle-maturing	Nov, 15	Dec, 5	Dec, 6	Apr, 1	Apr, 2	Apr, 22	Apr, 23	May, 20	May, 21	May, 26
(GDD)	(0)	(188)	(189)	(853)	(854)	(1120)	(1121)	(1494)	(1495)	(1602)
Late-maturing	Nov, 15	Dec, 8	Dec, 9	Apr, 5	Apr, 6	Apr, 25	Apr, 26	May, 23	May, 24	May, 30
(GDD)	(0)	(207)	(208)	(900)	(901)	(1173)	(1174)	(1555)	(1556)	(1665)

Notes: Referred to the year 2020.
Source: Tappi et al., 2023.

Table A.2. Phenological stages, weather events and critical limits of durum wheat in Apulia region.

Phenological Stage	Weather Event	Time Interval	Critical Limit	Reference
Sowing	Cold	From the first decade of November to the first decade of December	Temperature < 0 °C	Baldoni and Giardini, 2000; Angelini, 2007; Disciplinare di produzione integrata della Regione Puglia, 2021
Germination	Cold	From the second decade of November to the second decade of December	Temperature < 0 °C	
Stem elongation	Cold	From the second decade of March to the third decade of April	Temperature < 0 °C	Baldoni and Giardini, 2000; Angelini, 2007
Flowering	Cold	From the second decade of May to the first decade of June	Temperature < 0 °C	Angelini, 2007; Disciplinare di produzione integrata della Regione Puglia, 2021
	Heat, drought		Temperature > 30-31 °C	Angelini, 2007; Rezaei et al., 2015
Grain filling	Heat, drought	From the second decade of June to the first decade of July	Temperature > 34 °C	Angelini, 2007; Asseng et al., 2011; Rezaei et al., 2015; Zampieri et al., 2017; Makinen et al., 2018
All phases	Excessive rainfall	From first decade of November to the first decade of July	Rainfall > 40 mm/day	Makinen et al., 2018

Source: Tappi, Nardone, Santeramo, 2022.

A.2. Sensitivity analyses on the relationship between weather and yield

We investigate the relationship between weather variables and durum wheat yields during different phenological phases, using a non-linear panel regression. The five phenological stages of durum wheat are identified using the GDD approach, starting from sowing in mid-November (Miller et al., 2001). These stages include emergence, growth, anthesis, maturity, and final maturity. Additionally, we classify the wheat into early-, middle-, and late-maturing types, though we assume a standard sowing date of November 15 for all cultivars (see table A.3).

The subsequent econometric model reveals a strong relationship between durum wheat yields and temperature variations across different earliness categories, with a detailed analysis of each phenological phase (table A.3). During the starting phase, minimum temperatures negatively affect yields in a non-linear manner until they reach 8–9 °C for all earliness categories, while maximum temperatures have a beneficial impact up to 14–15 °C, beyond which yields begin to decline (table A.3). In the growing stage, minimum temperatures exert a consistent linear negative effect on yields (table A.3). Interestingly, during the anthesis stage, our findings present mixed results: minimum temperatures seem to enhance yields in a non-linear way, but only up to 7–9 °C for all varieties, after which the positive effect reverses. Notably, the influence of minimum temperatures on yields during this phase remains consistent across earliness categories. For maximum temperatures in the starting stage, there is a non-linear positive effect on yields for all varieties up to 14–15 °C, beyond which a decline is observed. Adverse effects of temperature become apparent in later stages, particularly during the maturity phase for late-maturing varieties and the end stages for early-maturing ones, with critical thresholds at 17 °C and 13 °C, respectively. Additionally, we assessed the statistical significance of weather coefficients across earliness and phenological phases. The results demonstrated a high level of confidence, with no significant differences among coefficients, indicating that temperature effects on yields are consistent across earliness categories within each phenological phase. This highlights a uniform sensitivity of durum wheat to temperature variations regardless of its maturity timeline.

Table A.3. Effects of earliness on the relationship between durum wheat yield and weather conditions.

	starting			growing			anthesis			maturity			end		
	EM	MM	LM	EM	MM	LM	EM	MM	LM	EM	MM	LM	EM	MM	LM
Minimum temperature	-0.21574***	-0.18915***	-0.14759***	-0.06015***	-0.05224***	-0.05544***	0.15038***	0.13949**	0.20802***	0.07918	-0.02572	0.00233	-0.34243*	-0.33464*	0.04429
	(0.05802)	(0.05257)	(0.04752)	(0.01944)	(0.01929)	(0.01927)	(0.05808)	(0.06170)	(0.06669)	(0.07492)	(0.07999)	(0.08207)	(0.19684)	(0.20040)	(0.20892)
Minimum temperature (sq)	0.01431***	0.01298***	0.00917***	-0.00322*	-0.00413**	-0.00298*	-0.00987**	-0.00865*	-0.01692***	-0.00880*	-0.00162	-0.00158	0.01720*	0.01595	-0.00285
	(0.00394)	(0.00364)	(0.00335)	(0.00173)	(0.00171)	(0.00170)	(0.00446)	(0.00455)	(0.00472)	(0.00456)	(0.00469)	(0.00465)	(0.01028)	(0.01008)	(0.01005)
Maximum temperature	0.48706***	0.33811***	0.25528***	0.01712	0.00387	0.00921	-0.02972	0.01816	0.13013	0.00072	-0.15447	-0.26802***	-0.37884*	-0.21556	-0.00099
	(0.11419)	(0.09905)	(0.08780)	(0.03572)	(0.03472)	(0.03381)	(0.07884)	(0.08382)	(0.08923)	(0.09370)	(0.09737)	(0.09974)	(0.22896)	(0.21750)	(0.22702)
Maximum temperature (sq)	-0.01716***	-0.01237***	-0.00938***	0.00180	0.00269*	0.00222	0.00275	0.00028	-0.00333	-0.00035	0.00456*	0.00836***	0.01483**	0.00983*	0.00423
	(0.00422)	(0.00375)	(0.00340)	(0.00158)	(0.00150)	(0.00143)	(0.00265)	(0.00274)	(0.00285)	(0.00271)	(0.00274)	(0.00273)	(0.00592)	(0.00549)	(0.00555)
Prov FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time trend	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Obs.	6,496	7,472	8,447	34,105	35,215	36,217	10,667	10,523	10,401	12,235	12,073	11,953	3,006	3,016	2,958
No. of prov	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30

Notes: EM, MM, and LM, indicate the early-, middle-, and late-maturing durum wheat earliness, respectively. Results show the estimates of the regressions model (1) for each year. Standard errors are shown in parenthesis. Phenological stages have been identified through the GDD approach, starting from November 15 as sowing date.

Source: Tappi et al., 2023.

The last model focuses on durum wheat yield in the Apulia region of Southern Italy. This estimation accounts for both spatial and temporal fixed effects and includes an error term. We also explore temporal and spatial autocorrelation to investigate whether weather events in one province affect adjacent provinces or if weather events from previous periods influence current yields. This analysis provides insight into the broader impacts of climate on wheat yields in both regional and national contexts (see tables A.4-A.5).

The analysis conducted for the Apulia region demonstrates a clear relationship between weather conditions and durum wheat production yields. Specifically, precipitation appears to have a negative impact on yields (table A.4), while temperature variables exhibit more complex effects. Minimum temperatures are associated with reduced yields, whereas maximum temperatures tend to enhance yields; however, both effects follow a nonlinear pattern. This highlights the inverted-U shape relationship observed in our findings, emphasizing the nonlinearity of weather impacts on agricultural outcomes. Additionally, minimum temperatures may influence contiguous provinces, suggesting spatial spillover effects. To better understand these dynamics, we estimated the model across different phenological phases of durum wheat, accounting for both spatial and temporal autocorrelations. Our findings indicate that the effects of weather variables are phase-specific: for instance, maximum temperatures during the germination stage and precipitation during the grain filling stage positively affect yields in a nonlinear way (table A.5). These results underline the importance of considering phenological phases and the specific timing of weather events in assessing their impact on crop production.

Table A.4. Effects of weather variables on durum wheat yield.

Variables	Panel prov FE time trend	Panel temporal correlation prov FE time trend	Panel spatial correlation prov FE time trend	Panel temporal correlation spatial correlation prov FE time trend
Temperature (min)	-0.00764	-0.00124	-0.46909***	-0.45553**
	(0.10641)	(0.11715)	(0.17058)	(0.18731)
Temperature (min) sq.	0.00049	-0.00023	0.00892*	0.01384**
	(0.0296)	(0.00320)	(0.00490)	(0.00544)
Temperature (max)	0.22572	0.28286*	0.61165**	0.66801**
	(0.14125)	(0.15378)	(0.25587)	(0.27703)
Temperature (max) sq.	-0.00523*	-0.00612**	-0.01530***	-0.02022***
	(0.00278)	(0.00299)	(0.00515)	(0.00568)
Precipitation	-0.01646**	-0.01625*	-0.03939**	-0.04670**
	(0.00799)	(0.00844)	(0.01819)	(0.01954)
Precipitation sq.	0.00008	0.00007	0.00019	0.00024
	(0.00006)	(0.00006)	(0.00017)	(0.00018)
Yield (lag)	-	0.10464***	-	-0.09290***
		(0.02153)		(0.03579)
Temperature (min) contig.	-	-	0.23065***	0.18642***
			(0.06565)	(0.07019)
Temperature (max) contig.	-	-	0.00822	0.04557
			(0.10765)	(0.11545)
Precipitation contig.	-	-	0.00537	0.00771
			(0.00704)	(0.00837)
Observations	1,837	1,638	914	833
Number of id	6	6	4	4

Notes: panel regression model was processed in STATA software. It includes provincial fixed effect, time trend, temporal (i.e., yield lag), and spatial (contiguous weather variables) autocorrelation. Standard errors in parentheses *** Significant at the 1 percent level. ** Significant at the 5 percent level. * Significant at the 10 percent level.
Source: Tappi, Nardone, Santeramo, 2023.

Table A.5. Effects of weather variables on yield by phase.

Variables	sowing	germination	stem elongation	flowering	grain filling
Yield (lag)	-0.11883	0.05952	0.17798*	-0.04474	0.09403
	(0.20660)	(0.20523)	(0.09219)	(0.18593)	(0.14041)
Temperature (min)	0.95845	-0.00051	0.50020	-1.32087	-0.65587
	(2.53724)	(1.74362)	(1.26379)	(4.06620)	(3.83238)
Temperature (min) sq.	-0.01783	0.01530	-0.01201	0.03550	0.02171
	(0.11363)	(0.08655)	(0.05223)	(0.10882)	(0.08353)
Temperature (max)	3.15220	23.00804**	-2.73726	7.62398	-1.65011
	(12.35641)	(10.88917)	(2.21349)	(8.51643)	(6.74553)
Temperature (max) sq.	-0.15964	-0.76330**	0.06023	-0.15868	0.01396
	(0.35336)	(0.33477)	(0.05582)	(0.15987)	(0.11320)
Precipitation	0.04601	-0.07450	-0.03735	-0.43463	0.42332*
	(0.12015)	(0.11228)	(0.07473)	(0.42173)	(0.24351)
Precipitation sq.	-0.00034	0.00054	0.00049	0.01188	-0.00826*
	(0.00088)	(0.00084)	(0.00101)	(0.01680)	(0.00463)
Temperature (min) contig.	1.05294**	0.86957**	0.62187***	0.52210	0.55304**
	(0.41397)	(0.35021)	(0.17188)	(0.35845)	(0.23765)
Temperature (max) contig.	0.38942	0.17524	-0.06474	0.22627	0.00512
	(1.25128)	(1.33537)	(0.34861)	(0.52741)	(0.37530)
Precipitation contig.	-0.05370	0.01278	-0.01394	-0.10017	-0.05635
	(0.05168)	(0.04199)	(0.03275)	(0.11446)	(0.04998)
Observations	42	44	125	43	67
Number of id	4	4	4	4	4

Notes: panel regression model was processed in STATA software. It includes provincial fixed effect, time trend, temporal (i.e., yield lag), and spatial (contiguous weather variables) autocorrelation. Standard errors in parentheses *** Significant

at the 1 percent level. ** Significant at the 5 percent level. * Significant at the 10 percent level.
Source: Tappi, Nardone, Santeramo, 2023.