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Final report on risks due to changing climate conditions with “maps of risk”

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1. Research activities

Changes in climate have animated again the debate on how assessing risk and novel techniques have been proposed. The changes in climate are altering (generally worsening) the exposure of economic activities to extreme/catastrophic weather events and natural disasters (Hay 2007). These climatic anomalies, being not well perceived, nor forecasted, have severe impacts on agricultural production and call for adequate coping strategies. Assessing extreme risks would improve the understanding of the farmers’ vulnerabilities to these. The rare events have a relatively low probability of occurrence and thus are positioned in the tails of the frequency distribution. The objective of this task has been to assess their probabilities, and how they impact the performances of agricultural activities, in terms of yields. The task, moving from the recent debate (Goodwin and Hungerford 2015; Ramsey 2020), has used flexible methods to model the tails of distributions of weather variables and how these affect yields.

1.1. Outcomes

The research activities allowed the identification of weather indexes for the assessment of the risks connected to changing climate conditions.

Simple weather indicators, listed in table 1, allow to monitor the evolution of temperature and precipitation. They were applied in Santeramo and Maccarone (2022) and Tappi et al. (2022, 2023).

Table 1. Simple weather indexes and their application.

		Application			
Indicator	Unit	Frequency	Coverage	Source	Reference
Maximum air temperature	°C	10-days, 2006-2019	Province (Puglia region)	ISPRA	Tappi et al. (2022)
		Daily, 2006-2020	Province (top 20 producing regions of wheat in Italy)	JRC MARS	Tappi et al. (2023)
Minimum air temperature	°C	10-days, 2006-2019	Province (Puglia region)	ISPRA	Tappi et al. (2022)
		Daily, 2006-2020	Province (top 20 producing regions of wheat in Italy)	JRC MARS	Tappi et al. (2023)
Diurnal temperature range	°C	Daily, 2006-2020	Province (top 20 producing regions of wheat in Italy)	JRC MARS	Tappi et al. (2023)
Average temperature	°C	Annual, 1920-2015	Country (Italy)	World Bank	Santeramo and Maccarone (2022)
Cumulative precipitation	mm	10-days, 2006-2019	Province (Puglia region)	ISPRA	Tappi et al. (2022)
		Annual, 1920-2015	Country (Italy)	World Bank	Santeramo and Maccarone (2022)
Precipitation	mm	Daily, 2006-2020	Province (top 20 producing regions of wheat in Italy)	JRC MARS	Tappi et al. (2023)

Complex indicators are used to capture the occurrence of catastrophic weather events, such as flood, drought, and frost. Following the definitions proposed in the Ministerial Decree No. 64591/2023, a flood event is a natural disaster resulting from torrential rains or flooding due to exceptional atmospheric events or from natural and artificial bodies of water invading surrounding areas, accompanied by transport and storage of solid and incoherent material. A drought event is an extraordinary precipitation scarcity as compared to the normal precipitation of the period, involving the lowering of soil water content below a critical moisture threshold and/or the impoverishment of water supply sources such that the implementing irrigation rescue interventions is not even possible. A frost event is a temperature drop lower than 0 °C due to the presence of cold air masses. A vast literature, reviewed in table 2, proposes several weather indicators to capture the occurrence of flood, drought, and frost events.

The Standardised Precipitation Evapotranspiration Index (SPEI) is a promising drought index since it includes a climatic water balance, such as fitting periods with zero precipitation (Stagge et al., 2015)[1].

Other complex weather indexes are crop-specific, such as crop water deficit and crop evapotranspiration[2]. The crop water deficit is the consequence of water loss from the leaf as

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[1] According to Vicente-Serrano et al., 2010, the SPEI is the difference between precipitation (P) and potential evapotranspiration (PET) in a month i:

$$D_i = P_i - PET_i \ where \ PET = 16K\left(\frac{10T}{I}\right)^m$$

where T is the monthly mean temperature (in °C), I is a heat index, m is a coefficient depending on I, and K is a correction factor calculated as a function of latitude and month i.
The index D_i provides a simple measure of the water surplus or deficit for the analysed month. According to Pei et al. (2020), D_i may be aggregated at different time scales:

$$D_n^k \sum_{i=0}^{t=1} (P_{n-1} - PET_{n-1}), t \geq k$$

where t is the monthly time scale and n is the number of calculations.
A three-parameter log-logistic probability density function was used to fit the established data series:

$$f(x) = \frac{\beta}{\alpha}\left(\frac{x-\gamma}{\alpha}\right)^{\beta-1}\left[1+\left(\frac{x-\gamma}{\alpha}\right)^{\beta}\right]^{-2}$$

where α, β and γ and are scale, shape, and origin parameters, respectively, for D values in the range ([γ; ∞[. The cumulative distribution function of a given time scale is given by:

$$F(x) = \left[1+\left(\frac{\alpha}{x-\gamma}\right)^{\beta}\right]^{-1}$$

The SPEI can be calculated as the standardised values of $F(x)$, as follows:

$$SPEI = \omega - \frac{c_0 + c_1\omega + c_2\omega}{1 + d_1\omega + d_2\omega + d_3\omega}$$

where $\omega = \sqrt{-2\ln(p)}$, $c_0 = 2.515517$, $c_1 = 0.802853$, $c_2 = 0.010328$, $d_1 = 1.432788$, $d_2 = 0.189269$, $d_3 = 0.001308$, p is the probability of exceeding a determined D value, $p = 1 - F(x)$. If $p > 0.5$, then p is replaced by $1 - p$ and the sign of the resultant SPEI is reversed.
In drought monitoring, a short timescale (e.g., 3 months) can be used to assess the meteorological drought in terms of intensity and frequency (Tan et al., 2015; Pei et al., 2020).

[2] Both weather indexes are applied in Tappi et al. (2023).

the stomata open to allow the uptake of carbon dioxide from the atmosphere for photosynthesis. The crop evapotranspiration is the rate of evapotranspiration from an extensive surface of 8 to 15 cm tall, green grass cover of uniform height, actively growing, completely shading the ground and not short of water. The indicator is highly crop- and phenological stage-specific and it is one of the main factors determining how much precipitation remains in the soil available for the crops[3] (Enenkel et al., 2019).

Table 2. Simple weather indexes and their application.

Event		Indicator		Threshold	Reference
Flood					
	soil moisture	5-days cumulated prec.		> 53 mm	Martina et al. (2006); Diakakis (2012)
	heavy prec.	daily prec.			
				> 25 mm	Kaiser et al. (2020)
				> 40 mm	Mäkinen et al. (2018)
				> 50 mm	Martina et al. (2006); Ma et al. (2021); Zhang et al. (2022)
				> 64.5 mm	Guhathakurta et al. (2011)
				> 122.6 mm	Wu et al. (2015)
Drought		SPEI		< -1	Danandeh Mehr et al. (2019)
Frost		daily temperature			
			durum wheat	< -4 °C	Barlow et al. (2015)
			almond	< -2.9 °C	Imani et al. (2012)
			apple	< -2.2 °C	Unterberger et al. (2018)
			grape wine	< -2 °C	Vitasse and Rebetez (2018)
			pear	< -2 °C	Drepper et al. (2022)
			peach	< -1.1 °C	Chen et al. (2016)
			apricot	< -1 °C	Pakkish and Tabatabaienia (2016)
			tomato	< -1 °C	Donderalp and Dursun (2022)
			maize	< 0 °C	Choudhury et al. (2019)
			orange	< 0 °C	Fitchett et al. (2014)
			kiwi	< 1.5 °C	Jeong et al. (2018)

[3] The crop evapotranspiration (ET_c) has been identified by the following formula:

$$ET_c = k_c * ET_0$$

where, k_c is the crop coefficient specific (i.e., property of plant used in predicting evapotranspiration) and ET_0 is the daily potential evapotranspiration (i.e., amount of water that would be evaporated and transpired by a specific crop). The variable k_c can be identified through the following formula proposed by Allen et al. (1998) for the correction of climatic factors:

$$k_c = k_{c(Tab)} + [0.04(u_2 - 2) - 0.004(RH_{min} - 45)]\left(\frac{h}{3}\right)^{0.3}$$

where $K_{c(Tab)}$ is a table crop coefficient highly related to each phenological stages, u_2 is wind speed at 2 m high, RH_{min} is mean value of minimum daily relative humidity, and h is plant height.

RH_{min} can be calculated using the following formula:

$$RH = \frac{vp}{svp} * 100$$

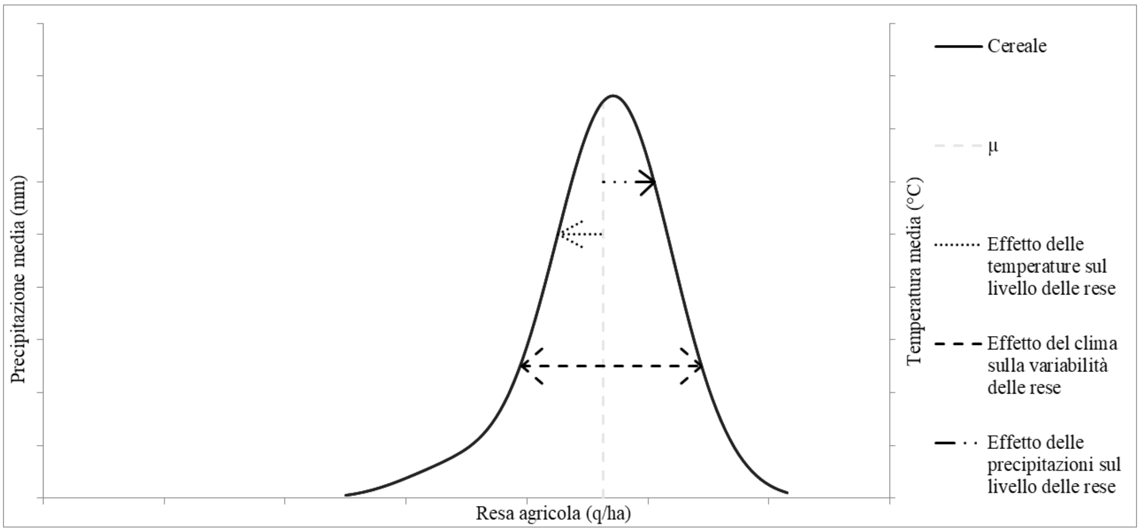
where vp is vapour pressure and the saturated vapour pressure (svp) can be obtained using the formula by Wang et al. (2007) and Suzuki et al. (2012):

$$svp = 0.6108 * Exp\frac{17.27 * avgtemperature}{avgtemperature + 237.3}$$

The research activities then allowed to examine the relationship between weather variables and yields.

The study of climate impacts on agricultural yields has been ongoing for at least half a century (Black and Thompson, 1978; Furuya and Koyama, 2005; Finger, 2010), analysing the effects of temperature and precipitation in various contexts (Thornton et al., 2009; Rowhani et al., 2011; Gaudin et al., 2015; Agnolucci and De Lipsis, 2019). The most studied aspects include the effects of temperature and precipitation on both the level and variability of agricultural yields. The literature suggests that rising temperatures and decreasing precipitation are potential causes of yield level reductions (Schlenker and Roberts, 2006; Cabas et al., 2010; Kim and Moschini, 2018; Lamonaca et al., 2021), while yield variability (Briche et al., 2014; Challinor et al., 2014; Ray et al., 2015) is attributed to increased temperatures and reduced precipitation (these findings are summarised in figure 1).

Figure 1. Relationship between weather variables and yields: a conceptual framework.



Source: Elaboration on Santeramo and Maccarone (2022).

In the literature review, presented in table 3, there are no contradictions in the results of the several studies, despite focusing on different crops—mostly cereals but also tree crops, legumes, and vegetables—and covering regions with significant developmental differences (e.g., Africa, America, Australia, Europe, India), underscoring the generality of the findings.

Table 3. Simple weather indexes and their application.

Authors	Year	Crop		Country		Period	Yield level		Yield variability	
		Cereals*	Other	Developed	Developing		T	P	T	P
Black and Thompson	1978	x	Beans	x		1870-1970	-			
Furuya and Koyama	2005	x	Soybean	x	x	1961-2000	-	+		
Schlenker and Roberts	2006	x		x		1950-2004	-			
Thornton et al.	2009	x	Beans		x	2000-2050	-	+		
Cabas et al.	2010	x	Soybean	x		1981-2006	-	+		
Finger	2010	x		x		1961-2006			+	+
Lobell and Burke	2010	x			x	2010-2050	-	+		
Peltonen-Sainio et al.	2010	x	Beet, rapeseed, potato	x		1975-2008	-	+		
Rowhani et al.	2011	x			x	1992-2005	-	+		
Sarker et al.	2012	x			x	1972-2009	-	+		
Barnwal and Kotani	2013	x			x	1971-2004	-	+		
Briche et al.	2014		Grapevine	x		1971-2000			+	+
Challinor et al.	2014	x		x		2010-2100	-	+	+	
Gaudin et al.	2015	x	Soybean	x		1982-2012	-	+		
Ray et al.	2015	x	Soybean	x	x	1979-2008			+	+
Trnka et al.	2016	x		x		1901-2012	-			
Kim and Moschini	2018	x	Soybean	x		1971-2015	-	+		
Agnolucci and De Lipsis	2019	x		x		1960-2020	-			
Fletcher et al.	2020	x		x		1900-2016	-	+		
Diffenbaugh et al.	2021	x		x		1991-2017	-	+		

Source: Elaboration on Santeramo and Maccarone (2022).

Note: * oats, wheat, maize, barley, rice, sorghum; The symbols used represent a decrease (-) or an increase (+) in the variables under examination.

1.2. Applications and impacts

The research activities allowed the realisation of geographical and sectoral maps of risks of interest for researchers and stakeholders.

Over the period between 2006 and 2020, Italy experienced 1,482 flood events, 2,557 moderate drought events, and 48,403 frost events (table 4). The frequency of flood events increased overtime (from 309 events in 2006-2010 to 461 in 2011-2015 and 712 in 2016-2020, table A.1), differently from the decreasing trend of drought (from 1,014 events in 2006-2010 to 769 in 2011-2015 and 774 in 2016-2020, table A.5) and frost events (from 17,688 events in 2006-2010 to 15,890 in 2011-2015 and 14,825 in 2016-2020, table A.9).

Table 4. Descriptive statistics of catastrophic weather events, 2006-2020.

Event	Number of events (2006-2020)	Mean (by year)	Std. dev. (by year)	Min (by year)	Max (by year)	Range (by year)
Flood	1,482	13	14	0	75	75
Drought	2,557	23	8	6	40	34
Frost	48,403	440	496	0	2,291	2,291

Source: Elaboration on data from the JRC MARS Meteorological Database.
Notes: Flood events identified as number of days with precipitation larger than 40 mm per day. Moderate drought events identified as number of days in a month with a Standardised Precipitation Evapotranspiration Index (SPEI) lower than -1. Frost events identified as number of days with daily minimum temperature lower than 0 °C.

Frost events were the most widespread along the Italian peninsula. More than two-thirds of the Italian provinces experienced at least one day per year with minimum temperatures lower than 0 °C. The years 2006, 2008, and 2017 were the coldest with respectively 93.6%, 90.9%, and 94.5% of provinces exposed to at least one frost event. Drought events were more random overtime, with some dry years (more than 90% of provinces observed at least one day of precipitation lower than 40 mm in 2006-2007, 2011, and 2016) and some wet periods (e.g., 2010, 2013-2014, 2018). Flood events occurred annually for at least one-third of the Italian provinces (table 5).

Table 5. Percentage of provinces affected by catastrophic weather events, by year.

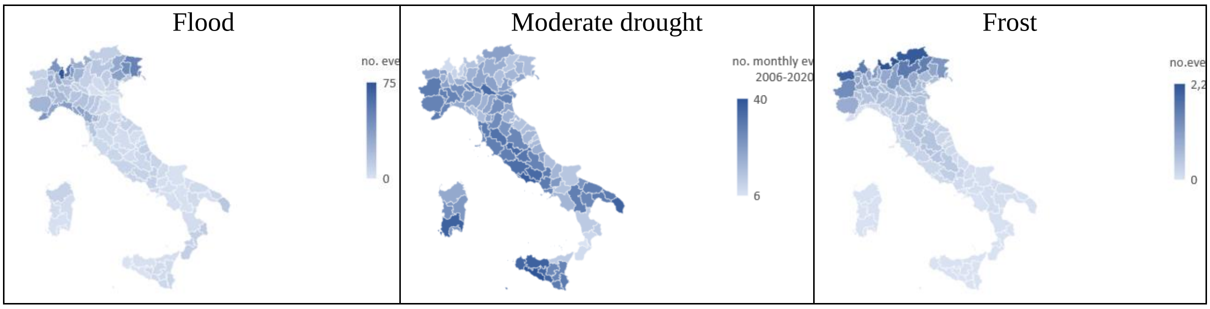
Event	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Flood	50.9	12.7	32.7	31.8	42.7	45.5	44.5	35.5	47.3	58.2	39.1	40.9	52.7	63.6	52.7
Drought	99.0	93.6	63.6	55.5	11.8	91.8	88.2	21.8	20.9	52.7	90.0	85.5	21.8	66.4	40.0
Frost	93.6	84.5	90.9	88.2	88.2	79.1	89.1	80.0	84.5	75.5	77.3	94.5	81.8	86.4	75.5

Source: Elaboration on data from the JRC MARS Meteorological Database.
Notes: Flood events identified as number of days with precipitation larger than 40 mm per day. Moderate drought events identified as number of days in a month with a Standardised Precipitation Evapotranspiration Index (SPEI) lower than -1. Frost events identified as number of days with daily minimum temperature lower than 0 °C.

The incidence of flood events was greater in Northern provinces than in Southern provinces.

Flood events tended to be more frequent in provinces of Lombardia and Friuli-Venezia Giulia regions and frost events in provinces of Valle d’Aosta, Piemonte, Lombardia, Trentino Alto-Adige, and Friuli-Venezia Giulia regions. Moderate drought events occurred the most in Western provinces (especially in Lazio, Sicilia, and Sardegna regions) than in Eastern provinces (Puglia region being an exception) (figure 2). Figures A.1, A.2, A.3 maps the number of catastrophic weather events by period.

Figure 2. Maps of the number of catastrophic weather events, 2006-2020.



Source: Elaboration on data from the JRC MARS Meteorological Database.
Notes: Flood events identified as number of days with precipitation larger than 40 mm per day. Moderate drought events identified as number of days in a month with a Standardised Precipitation Evapotranspiration Index (SPEI) lower than -1. Frost events identified as number of days with daily minimum temperature lower than 0 °C.

Over the period between 2006 and 2020, Varese, Como, and Udine were the provinces most exposed to flooding (with 75, 55, and 50 events, respectively) (table 6). Varese and Como are among the top ten provinces affected by flood events, but from 2016 also Massa-Carrara, Lucca, and Pistoia provinces (in Toscana region) started to experience the effects of flood events (table A.4).

Agrigento and Latina provinces were the most hit by moderate droughts (with 40 and 38 events, respectively) followed by Lecce, Medio Campidano, and Palermo (37 events each) (table 6). While provinces in the Centre of Italy are among the most affected by moderate drought events during the period between 2006 and 2010, the occurrence of these events became more frequent in provinces of Sicilia and Sardegna regions since 2011 (table A.8).

Sondrio, Bolzano, and Aosta were the coldest provinces with 2,291, 2,194, and 2,087 frost events, respectively (table 6). The top ten provinces most affected by frost events remained the same over the time period (table A.12).

More descriptive statistics are in tables A.2-A.3, A.6-A.7.

Table 6. Top ten provinces experiencing catastrophic weather events, 2006-2020.

	Number of events (2006-2020)	Mean (by year)	Std. dev. (by year)	Min (by year)	Max (by year)	Range (by year)
Flood						
Varese	75	5	2	1	7	6
Como	55	4	2	1	7	6
Udine	50	3	3	0	11	11
Pordenone	45	3	3	0	9	9
Gorizia	41	3	1	1	6	5
Imperia	41	3	2	0	6	6
Lecco	41	3	2	1	8	7
Verbano-Cusio-Ossola	41	3	2	0	7	7
Genova	37	3	3	0	10	10
Treviso	35	2	2	0	7	7
Drought						
Agrigento	40	3	2	0	7	7
Latina	38	3	2	0	8	8
Lecce	37	2	2	0	7	7
Medio Campidano	37	2	2	0	9	9
Palermo	37	2	2	0	6	6
Caltanissetta	36	2	2	0	6	6
Trapani	36	2	2	0	6	6
Frosinone	35	2	3	0	9	9
Mantova	35	2	2	0	5	5
Terni	35	2	3	0	10	10
Frost						
Sondrio	2,291	152.73	9.18	132	164	32
Bolzano	2,194	146.27	8.29	124	155	31
Aosta	2,087	139.13	11.68	118	161	43
Trento	1,675	111.67	8.60	86	121	35
Verbano-Cusio-Ossola	1,649	109.93	12.73	90	135	45
Belluno	1,596	106.40	11.37	72	120	48
Torino	1,376	91.73	10.68	76	113	37
Udine	1,231	82.07	16.23	30	97	67
Como	1,202	80.13	14.70	45	100	55
Brescia	1,120	74.67	16.62	28	96	68

Source: Elaboration on data from the JRC MARS Meteorological Database.
Notes: Flood events identified as number of days with precipitation larger than 40 mm per day. Moderate drought events identified as number of days in a month with a Standardised Precipitation Evapotranspiration Index (SPEI) lower than -1. Frost events identified as number of days with daily minimum temperature lower than 0 °C.

The research activities also allowed to understand how weather variables affect level and variability of cereal yields. We employ a multiple regression approach to analyse the impact of historical temperature and precipitation changes on the distributions of major cereal crops in Italy. Our method essentially involves utilising three specific econometric specifications. First, we consider the overall effects of climate on all examined crops, assuming a nonlinear relationship between cereal yields and both temperature and precipitation. Second, we implement fixed effects to account for the influence of climatic factors on each crop individually. Finally, in the third specification, dummy variables are included to represent crop-specific temperature and precipitation effects, modelled linearly in relation to these climatic variables.

The results, reported in table 7, demonstrate that the relationships between climatic trends and cereal yields align closely with findings from previous scientific studies (Furuya and Koyama, 2005; Finger, 2010; Sarker et al., 2012; Trnka et al., 2016).

Table 7. Estimates on yield levels and variability.

Weather Variables	Yield Level (1)			Yield Variability (2)		
	I	II	III	I	II	III
T	7.605	-43.87	-37.33	0.326***	1.074**	0.937**
	(5.127)	(71.91)	(70.12)	(0.0367)	(0.514)	(0.419)
$(T)^2$	0.153**	0.188**	0.188**	-0.00196***	-0.00247***	-0.00247***
	(0.0625)	(0.0795)	(0.0773)	(0.000448)	(0.000568)	(0.000462)
P	102.9***	103.8***	102.4***	0.392***	0.378**	0.358***
	(20.85)	(20.90)	(20.51)	(0.149)	(0.149)	(0.122)
$(P)^2$	-0.0487***	-0.0492***	-0.0492***	-0.000183**	-0.000176**	-0.000176***
	(0.0102)	(0.0103)	(0.00998)	(7.32e-05)	(7.33e-05)	(5.96e-05)
T* Crop Dummy						
Oats		1.055			0.00202	
Wheat		-1.768			0.0442	
Maize		-28.50***			0.597***	
Barley		-13.04*			0.201***	
Rice		3.041			-0.0239	
P* Crop Dummy						
Oats		-0.303			0.0148	
Wheat		-0.424			0.0191	
Maize		9.689**			0.0709***	
Barley		0.415			0.0158	
Rice		-0.974			-0.00344	
Years		0.524			-0.00762*	
Crop Fixed Effects	No	Yes	Yes	No	Yes	Yes
Constant	-282.0***	-1,337	-1,329	10.43**	18.13*	18.19**
	(63.68)	(1,434)	(1,395)	(4.704)	(10.25)	(8.328)
Observations	576	576	576	576	576	576

Notes: Acronyms refer to temperature (T), precipitation (P); (1) detrended yields, (2) bootstrap standard deviation of detrended yields; standard errors in parentheses. ***p<0.01, **p<0.05, *p<0.1. Source: Elaborated from CCKP, INEA, ISTAT, MIPAAF data.

Specifically, no generalised temperature effect was observed across the six cereals analysed, although rising temperatures were found to decrease yields for maize and barley, showing a non-linear trend (Schlenker and Roberts, 2006; Lobell and Burke, 2010). Regarding precipitation, a positive, non-linear correlation was noted, where reductions in rainfall led to yield decreases, with maize being the most affected (Rowhani et al., 2011; Agnolucci and De Lipsis, 2019). In terms of variability, the standard deviation of yields was positively correlated with temperature trends, particularly for maize and barley, again following a non-linear relationship (Barnwal and Kotani, 2013; Diffenbaugh et al., 2021). This indicates that higher temperatures increase yield variability. Similarly, reduced precipitation generally heightened variability, with maize being disproportionately impacted (Ray et al., 2015; Trnka et al., 2016). In summary, trends in temperature and precipitation significantly influence both average yield levels and their variability, albeit differently across crops, with maize showing the greatest sensitivity to ongoing climate changes. This analysis has quantified the tangible losses experienced by the Italian cereal sector as a consequence of climate change.

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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).
7. Santeramo, F. G., Lamonaca, E., Maccarone, I., & Tappi, M. (2024). Extreme weather events and crop insurance demand. *Heliyon*, *10*(7). DOI: 10.1016/j.heliyon.2024.e27839 [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

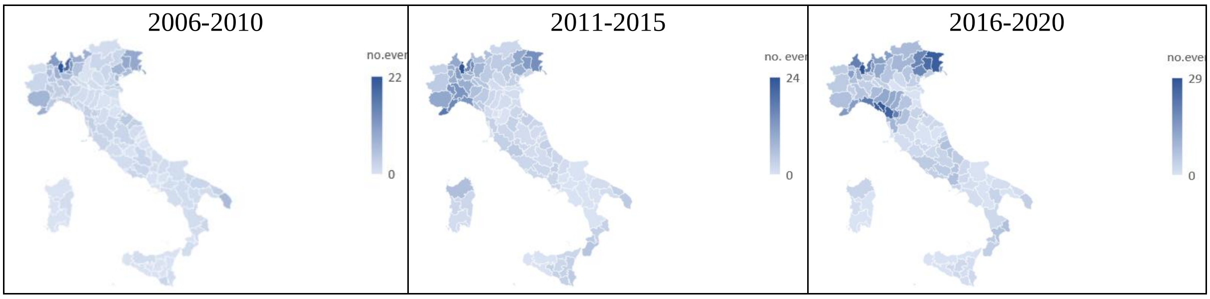
A.1. Occurrence of flood events

Table A.1. Descriptive statistics of flood events, 2006-2020.

Period	Number of events	Mean (by year)	Std. dev. (by year)	Min (by year)	Max (by year)	Range
2006-2020	1,482	13	14	0	75	75
2006-2010	309	3	4	0	22	22
2011-2015	461	4	5	0	24	24
2016-2020	712	6	7	0	29	29

Source: Elaboration on data from the JRC MARS Meteorological Database.
Notes: Flood events identified as number of days with precipitation larger than 40 mm per day.

Figure A. 1 Number of flood events by province and period.



Source: Elaboration on data from the JRC MARS Meteorological Database.
Notes: Flood events identified as number of days with precipitation larger than 40 mm per day.

Table A.2. Top ten provinces experiencing flood events, 2006-2020.

Province	Number of events	Mean (by year)	Std. dev. (by year)	Min (by year)	Max (by year)	Range
Varese	75	5	2	1	7	6
Como	55	4	2	1	7	6
Udine	50	3	3	0	11	11
Pordenone	45	3	3	0	9	9
Gorizia	41	3	1	1	6	5
Imperia	41	3	2	0	6	6
Lecco	41	3	2	1	8	7
Verbano-Cusio-Ossola	41	3	2	0	7	7
Genova	37	3	3	0	10	10
Treviso	35	2	2	0	7	7

Source: Elaboration on data from the JRC MARS Meteorological Database.
Notes: Flood events identified as number of days with precipitation larger than 40 mm per day.

Table A.3. Annual number of flood events for top ten provinces, 2006-2020.

Province	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Varese	3	1	5	7	6	3	4	6	7	4	6	5	5	6	7
Como	1	1	6	6	5	2	1	5	5	2	4	4	3	3	7
Udine	1	0	3	4	1	0	4	2	6	2	1	4	4	11	7
Pordenone	2	0	4	2	1	1	4	3	4	0	0	3	4	9	8
Gorizia	2	1	2	2	4	3	3	3	3	2	1	3	2	6	4
Imperia	1	0	1	3	3	3	4	3	6	2	1	1	4	6	3
Lecco	1	1	2	2	6	1	2	4	5	2	1	2	2	2	8
Verbano-Cusio-Ossola	1	1	3	3	3	1	0	3	5	1	2	1	7	7	3
Genova	1	1	0	1	0	2	4	1	5	1	2	2	2	10	5
Treviso	2	1	4	0	0	1	2	2	4	0	3	2	2	7	5

Source: Elaboration on data from the JRC MARS Meteorological Database.
Notes: Flood events identified as number of days with precipitation larger than 40 mm per day.

Table A.4. Top ten provinces experiencing flood events by period.

Province	Number of events
	2006-2010
Varese	22
Como	19
Trieste	13
Lecco	12
Gorizia	11
Monza e Brianza	11
Verbano-Cusio-Ossola	11
Pordenone	9
Udine	9
Imperia	8
Novara	8
Sondrio	8
	2011-2015
Varese	24
Imperia	18
Como	15
Savona	15
Gorizia	14
Lecco	14
Udine	14
Alessandria	13
Asti	13
Genova	13
	2016-2020
Varese	29
Massa-Carrara	28
La Spezia	27
Udine	27
Lucca	26
Pordenone	24
Como	21
Genova	21
Pistoia	20
Verbano-Cusio-Ossola	20

Source: Elaboration on data from the JRC MARS Meteorological Database.
Notes: Flood events identified as number of days with precipitation larger than 40 mm per day.

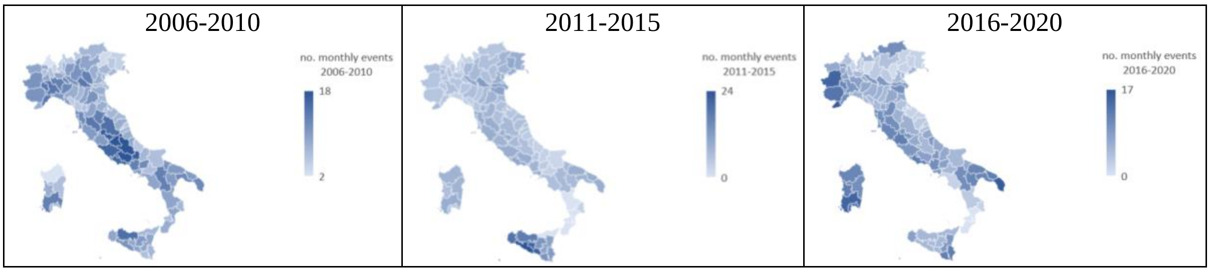
A.2. Occurrence of drought events

Table A.5. Descriptive statistics of moderate drought events, 2006-2020.

Period	Number of events	Mean (by year)	Std. dev. (by year)	Min (by year)	Max (by year)	Range
2006-2020	2,557	23	8	6	40	34
2006-2010	1,014	9	4	2	18	16
2011-2015	769	7	4	0	24	24
2016-2020	774	7	4	0	17	17

Source: Elaboration on data from the JRC MARS Meteorological Database.
Notes: Moderate drought events identified as number of days in a month with a Standardised Precipitation Evapotranspiration Index (SPEI) lower than -1.

Figure A. 2 Number of moderate drought events by province and period.



Source: Elaboration on data from the JRC MARS Meteorological Database.
Notes: Moderate drought events identified as number of days in a month with a Standardised Precipitation Evapotranspiration Index (SPEI) lower than -1.

Table A.6. Top ten provinces experiencing moderate drought events, 2006-2020.

Province	Number of events	Mean (by year)	Std. dev. (by year)	Min (by year)	Max (by year)	Range
Agrigento	40	3	2	0	7	7
Latina	38	3	2	0	8	8
Lecce	37	2	2	0	7	7
Medio Campidano	37	2	2	0	9	9
Palermo	37	2	2	0	6	6
Caltanissetta	36	2	2	0	6	6
Trapani	36	2	2	0	6	6
Frosinone	35	2	3	0	9	9
Mantova	35	2	2	0	5	5
Terni	35	2	3	0	10	10

Source: Elaboration on data from the JRC MARS Meteorological Database.
Notes: Moderate drought events identified as number of days in a month with a Standardised Precipitation Evapotranspiration Index (SPEI) lower than -1.

Table A.7. Annual number of moderate drought events for top ten provinces, 2006-2020.

Province	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Agrigento	1	1	2	2	5	7	7	4	5	1	2	1	0	0	2
Latina	4	8	4	0	0	5	2	0	1	2	1	6	0	3	2
Lecce	2	5	4	1	0	1	3	3	0	2	5	7	0	2	2
Medio Campidano	3	2	5	2	1	1	1	0	2	5	1	9	0	3	2
Palermo	4	1	3	2	5	6	4	3	4	0	2	1	0	0	2
Caltanissetta	1	1	0	3	4	6	6	5	5	0	2	1	0	0	2
Trapani	6	1	0	0	2	5	5	4	4	1	2	2	0	1	3
Frosinone	4	9	5	0	0	4	3	0	0	2	1	5	0	2	0
Mantova	5	5	1	3	0	3	5	0	0	4	1	5	0	2	1
Terni	4	10	3	0	0	4	4	0	0	1	1	7	0	1	0

Source: Elaboration on data from the JRC MARS Meteorological Database.
Notes: Moderate drought events identified as number of days in a month with a Standardised Precipitation Evapotranspiration Index (SPEI) lower than -1.

Table A.8. Top ten provinces experiencing moderate drought events by period.

Province	Number of events
	2006-2010
Frosinone	18
L’Aquila	18
Rieti	18
Isernia	17
Terni	17
Latina	16
Roma	16
Palermo	15
Perugia	15
Alessandria	14
Asti	14
Mantova	14
Savona	14
Siena	14
	2011-2015
Agrigento	24
Caltanissetta	22
Trapani	19
Palermo	17
Enna	13
Ragusa	13
Mantova	12
Siracusa	12
Catania	11
Ferrara	11
Rovigo	11
	2016-2020
Carbonia-Iglesias	17
Imperia	16
Lecce	16
Medio Campidano	15
Torino	15
Cagliari	13
Cuneo	13
Ogliastra	13
Brindisi	12
Latina	12
Oristano	12
Ragusa	12
Siracusa	12
Viterbo	12

Source: Elaboration on data from the JRC MARS Meteorological Database.
Notes: Moderate drought events identified as number of days in a month with a Standardised Precipitation Evapotranspiration Index (SPEI) lower than -1.

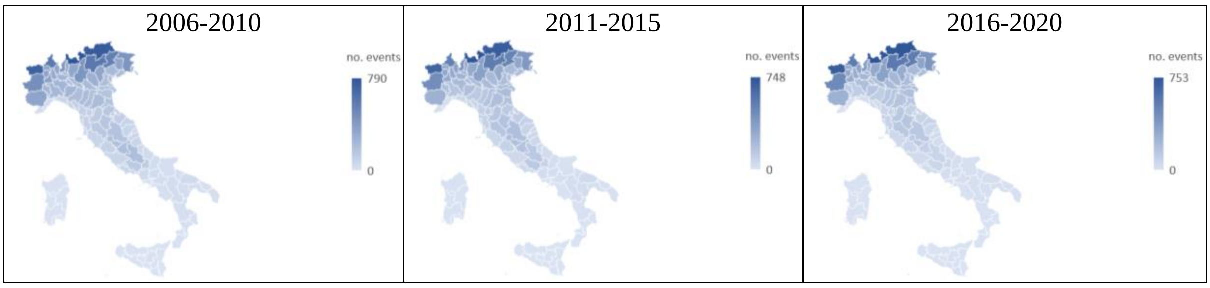
A.3. Occurrence of frost events

Table A.9. Descriptive statistics of frost events, 2006-2020.

Period	Number of events	Mean (by year)	Std. dev. (by year)	Min (by year)	Max (by year)	Range
2006-2020	48,403	440	496	0	2,291	2,291
2006-2010	17,688	161	172	0	790	790
2011-2015	15,890	144	160	0	748	748
2016-2020	14,825	135	166	0	753	753

Source: Elaboration on data from the JRC MARS Meteorological Database.
Notes: Frost events identified as number of days with daily minimum temperature lower than 0 °C.

Figure A. 3 Number of frost events by province and period.



Source: Elaboration on data from the JRC MARS Meteorological Database.
Notes: Frost events identified as number of days with daily minimum temperature lower than 0 °C.

Table A.10. Top ten provinces experiencing frost events, 2006-2020.

Province	Number of events	Mean (by year)	Std. dev. (by year)	Min (by year)	Max (by year)	Range
Sondrio	2,291	152.73	9.18	132	164	32
Bolzano	2,194	146.27	8.29	124	155	31
Aosta	2,087	139.13	11.68	118	161	43
Trento	1,675	111.67	8.60	86	121	35
Verbano-Cusio-Ossola	1,649	109.93	12.73	90	135	45
Belluno	1,596	106.40	11.37	72	120	48
Torino	1,376	91.73	10.68	76	113	37
Udine	1,231	82.07	16.23	30	97	67
Como	1,202	80.13	14.70	45	100	55
Brescia	1,120	74.67	16.62	28	96	68

Source: Elaboration on data from the JRC MARS Meteorological Database.
Notes: Frost events identified as number of days with daily minimum temperature lower than 0 °C.

Table A.11. Annual number of frost events for top ten provinces, 2006-2020.

Province	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Sondrio	148	160	162	157	163	164	152	153	132	147	151	151	143	164	144
Bolzano	144	152	155	143	155	147	142	152	124	137	149	148	141	150	155
Aosta	136	139	140	145	156	118	128	161	129	130	149	145	137	147	127
Trento	121	115	120	115	118	114	105	113	86	118	113	114	109	105	109
Verbano-Cusio-Ossola	113	93	114	128	135	99	109	123	90	99	116	113	111	108	98
Belluno	115	103	101	113	114	113	101	107	72	115	111	107	105	99	120
Torino	95	77	84	96	108	77	90	113	76	91	91	100	94	96	88
Udine	96	80	72	91	94	97	93	85	30	90	76	83	82	82	80
Como	97	64	69	92	100	95	83	92	45	84	73	83	74	81	70
Brescia	93	68	76	91	96	85	83	84	28	70	71	69	75	72	59

Source: Elaboration on data from the JRC MARS Meteorological Database.
Notes: Frost events identified as number of days with daily minimum temperature lower than 0 °C.

Table A.12. Top ten provinces experiencing flood events by period.

Province	Number of events
	2006-2010
Sondrio	790
Bolzano	749
Aosta	716
Trento	589
Verbano-Cusio-Ossola	583
Belluno	546
Torino	460
Udine	433
Brescia	424
Como	422
	2011-2015
Sondrio	748
Bolzano	702
Aosta	666
Trento	536
Verbano-Cusio-Ossola	520
Belluno	508
Torino	447
Como	399
Udine	395
Brescia	350
	2016-2020
Sondrio	753
Bolzano	743
Aosta	705
Trento	550
Verbano-Cusio-Ossola	546
Belluno	542
Torino	469
Udine	403
Como	381
Brescia	346

Source: Elaboration on data from the JRC MARS Meteorological Database.
Notes: Frost events identified as number of days with daily minimum temperature lower than 0 °C.