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Earliness, phenological phases and yield-temperature relationships: evidence from durum wheat in Italy

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Abstract. The impacts of extreme weather events on crop production are largely heterogeneous along the timing dimension of the shocks, and the varieties being affected. We investigate the yield-temperature relationships for three categories of earliness of durum wheat: early-maturing, middle-maturing, and late-maturing. We disentangle the time dimension distinguishing five phenological stages, as identified by the Growing Degree Days approach. Our panel regression models show that the starting, growing, and anthesis stages are sensitive to changes in minimum temperatures, regardless of wheat earliness. Raises in maximum temperatures during the starting stage are associated with increases in yields until a certain threshold above of which decrease; the opposite is true for increases in maximum temperatures in the maturity stage for late-maturing varieties, and in the end stage for early-maturing varieties. Results imply that farmers and policymakers may adopt ex-ante and ex-post risk management strategies, i.e., choice of variety to avoid severe yield losses and incentives to crop insurance uptake, respectively.

Keywords: climate change, crop insurance, growing degree days, risk management, weather index.
JEL codes: G22, Q18, .

INTRODUCTION

The climate variability and the increased frequency of extreme weather events threaten the agricultural sector (Auci et al., 2021). The simulations on projected yields under climate change conditions show losses in crop production (Challinor et al., 2014). In turn, these, may impact the market dynamics with price increases and changes in firms' profitability margins (Stevanovic et al., 2016). The risk management interventions subsidised by the Common Agricultural Policy (CAP) of European Union (EU), e.g., crop insurances, mutual funds, may help farmers to cope with the potential losses due to climatic changes (Severini et al., 2016; Meuwissen et al., 2018; Shirsath et al., 2019; Giampietri et al., 2020; Cordier and Santeramo, 2020; Rippo and Cerroni, 2022), even better if combined with other ex-ante practices, e.g., agroecological strategies (Altieri et al., 2015). The weather-index insurances (WIIs) emerged as promising tools to indemnify farmers affected by weather damages (Anghileri et al., 2022). The working principle of the WIIs is a compensation based on a proxy (the weather index) correlated with potential yield losses (Abdi et al., 2022). The WIIs may contribute solving the market failures due to moral hazard and adverse selection issues, which are common in traditional indemnity insurance (Santeramo, 2019; Bucheli et al., 2022). The main threat to the well-functioning WIIs relies on the possible low correlation between triggered pay-outs and the occurrence of loss events, a peculiarity referred to as 'basis risk' (Cesarini et al., 2021). The basis risk may assume multiple forms. The temporal basis risk may result from the discrepancy between the timing of the weather index fails and the evolution of the crop growth stages (Masiza et al., 2022). The phenology information collected in publicly available datasets (e.g., through satellite remote sensors) may help reduce the temporal basis risk (Dalhaus et al., 2018; Afshar et al., 2021). Indeed, the phenological stages show different susceptibilities to the weather conditions, a relevant aspect for the weather index definition. As for durum wheat, the timing of the undesired weather events matter. For instance, low temperatures are detrimental in all stages of growth, but the most severe negative impacts are observed during the reproductive stage (Barlow et al., 2015). High temperatures severely compromise the physiological processes during the flowering and grain filling stages (Rezaei et al., 2015; Makinen et al., 2018, Gagliardi et al., 2020). As a matter of fact, taking into consideration the phenological stages within which the weather event occur is crucial to understand the weather-yields relationships better: this concept directly translates into better modelling of the temporal basis risk. Although remote sensing imagery represents a promising technique for identifying phenological stages, many factors, such as the atmospheric conditions (e.g., clouds) or the biotic and abiotic environmental perturbations, may also be relevant to analyse the physiological process (Zeng et al., 2020), but are complex in nature and computation. On the other hand, a fixed calendar approach may be oversimplistic and misleading. A second-best solution is to use the Growing Degree Days (GDD), adopted to schedule management activities. It represents a suitable method to predict specific crop stages based on the amount of daily temperature degree (Miller et al., 2001). Conradt et al., 2015 showed that the GDD approach accurately identifies the phenological phases. However, the timing of the phenological stages is not homogenous across varieties. Apart from the studies just mentioned, the literature on the role of varieties in shaping the relationships between yield and weather is quite limited. Thus, departing from a vast literature on the yield-weather nexus (Di Falco et al., 2012; Powell and Reinhard, 2016; Delerce et al., 2016; Chavas et al., 2019), we deepen on the heterogeneities that the yield-temperatures relationship may show across different phenological stages and earliness of durum wheat, hereafter defined as early-maturing, middle-maturing, and late-maturing. Building up the works of Tappi et al. (2022), who show the need to collect more refined data to investigate the relationships between yields and weather variables, and of Tappi et al. (2022), who focus on the role of temporal and design approaches in yield-weather assessment, the aim of our paper is to assess whether the relationships yield-temperature control for three categories of durum wheat earliness (i.e., early-maturing, middle-maturing, and late-maturing) among five phenological stages identified by the GDD approach, focusing on the most representative Italian provinces in terms of durum wheat production. Apart from the new knowledge, our paper has direct implications for farmers aiming to adopt ex-ante risk management strategies (e.g., choice of variety) and for policymakers planning ex-post risk management strategies (e.g., incentives to crop insurance uptake). The Italian participation level in crop insurance schemes is still low, limited to few products, and concentrated in few areas (Santeramo, 2018, 2019; Coletta et al., 2018). Therefore, the focus on the yield-temperature relationship may directly speak with the ongoing debate on how to improve the attractiveness of innovative insurances in a more and more warming climate change scenario.

DATA AND METHODOLOGY

Durum wheat is the main crop in the Mediterranean area for making pasta, couscous, semolina, and other products (Carucci et al., 2020). We collected yields and weather data from 2006 to 2020 of 30 main durum wheat-producing Italian provinces, located in Central and Southern Italy (Figure 1, in the Appendix). Specifically, yearly durum wheat yield data (quintals of production/cultivated hectares) have been collected from the National Institute of Statistics (ISTAT). In contrast, daily weather data have been collected from JRC - Agri4Cast

Table 1. Descriptive statistics of daily temperatures and yearly yield variables from 2006 to 2020 among 30 main durum-wheat producing Italian provinces.

Variable (unit)	Obs.	Mean	Median	St. dev	Min	Max
Maximum temperature (°C)	68,832	13.55749	13.63	4.59804	-5.336364	32.98
Minimum temperature (°C)	68,832	5.899284	6.07	3.919422	-11.65	19.95
Yield (q/ha)	68,299	36.81634	33	12.98301	17	81.42377

Meteorological database of European Commission that includes maximum temperatures (°C) and minimum temperatures (°C).

Descriptive statistics of the dataset are shown in Table 1. More specifically, maximum temperatures show a mean value of 13.5 °C, a median value of 13.6 °C, in a range between -5.3 °C and 33 °C; minimum temperatures show a mean value of 5.9 °C, a median value of 6.1 °C, in a range between -11.6 °C and 19.9 °C,

Furthermore, maximum temperatures exceed 30 °C in some Southern provinces, e.g., Agrigento, Caltanissetta, Catania, Enna, Matera, Palermo, Trapani, while minimum temperatures exceed -2 °C in some Northern provinces, e.g., Bologna, Ferrara, Perugia, Pisa, Ravenna, Rovigo, Siena (Table 2, in the Appendix). We selected weather variables within the timeframe of the wheat production cycle. Several approaches are available to assess econometrically the weather impacts on society and the economy: cross-sections, linear and non-linear panel, long-differences, and partitioning variation (Hsiang, 2016; Kolstad and Moore, 2020). Cross-sectional and panel regression analyses are the most used to assess the climate impacts on agriculture (Carter et al., 2018). Generally, panel model approach uses crop yields as the output of production function, while the cross-section uses a proxy for land productivity, e.g., revenue or profit (Blanc and Schlenker, 2020). According to Hsiang (2016), climate may affect social outcomes in two ways: directly, i.e., the effects of weather in a certain time, and indirectly (i.e., belief effect), i.e., the consequent effects of weather on decisions and actions also referred to as adaptation. Belief effects and other unobservable variables may cause bias in estimates (Hsiang, 2016). In this complex scenario and considering the trade-off among econometrics models, the panel approach presents some advantages for controlling unobserved omitted variables, removing a possible source of bias (Hsiang, 2016; Kolstad and Moore, 2020). Moreover, nonlinear panel models with fixed effects may capture partially long-run adaptive response to climate change (Carter et al., 2018), also contributing to overcoming the main limitations of panel regression: the short-run response to weather fluctuations (Kolstad and Moore, 2020). Therefore, our yield response equation is based on a non-linear panel regression:

$$y_{it} = f(w_{it};\boldsymbol{\beta}) + \alpha_i + \alpha_t + \varepsilon_{it} \tag{1}$$

where y_{it} represents the vector of durum wheat yield data for the 30 main Italian provinces (i) in terms of production volumes and time horizon covered (t). The function $f(w_{it};\beta)$ is explained in the formula (2) below. The estimated coefficients (in bold) are collected in the matrix of first and second-order coefficients noted as $\boldsymbol{\beta}$, whereas α_i and α_t are the vectors of the location-specific and year-specific fixed effects, controlling for unobserved heterogeneity over space and time. The error term is noted by the ε_{it} (Hsiang, 2016; Tack et al., 2015; Kolstad and Moore, 2020). Five phenological stages of durum wheat have been identified through the GDD approach, starting from the sowing date in the middle of November for wheat crop cultivated in the Mediterranean area (Miller et al., 2001): (i) starting, from emergence to two leaves unfolded; (ii) growing, from the end of two leaves unfolded to the beginning of anthesis (first anthers are visible); (iii) anthesis, from the beginning of anthesis to beginning of seed fill; (iv) maturity, from the beginning of seed fill to dough stage; (v) end, from dough stage to full maturity. The GDD approach predicts plants stages from seeding to maturity using the accumulation of heat or temperature units above a threshold or base temperature below which no growth occurs (Miller et al., 2001). The function $f(w_{it};\beta)$ is explicated as follows:

$$f(w_{it};\beta) = \sum_{x=1}^{2}\sum_{s=1}^{s=5}\beta_{xs}{}^{x}\, tmin_{it}{}^{x} + \\ + \sum_{x=1}^{2}\sum_{s=1}^{s=5}\beta_{xs}{}^{x}\, tmax_{it}{}^{x} \tag{2}$$ [1]

[1] We focused on how the temperatures may affect the yields, considering the precipitations as control factor mainly because its effect on yields is difficult to catch (being affected by other variables such as soil texture, management practices, irrigation, etc.). A single rain event may impact on a smaller portion of territory than changes in temperatures affecting entire areas. Therefore, the evaluation of the effect of precipitation on the yields needs of further investigation. Moreover, we controlled for the market shocks, i.e., on how unfavourable years in terms of durum wheat price. The results are robust.

Table 3. 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)

Note: Referred to the year 2020.

where $tmin_{it}$ and $tmax_{it}$, are the daily minimum and maximum temperatures across space (i) and time (t). The index s (s = {1,2,3,4,5}) indicates the phenological stage of durum wheat. The apex x indicates the linearity of the term. Furthermore, based on phenology calculation combined with the Universal Growth Staging Scale reported in Miller et al. (2001) for the wheat crop, we identified three categories of earliness, i.e., early-maturing, middle-maturing, and late-maturing, also identifying the dates of occurrence of phenological stages (Table 3).

We assume that the sowing date is the same for all varieties (i.e., November 15[2]), although it represents a limit of our paper. However, it is useful to assess yield-temperature relationships among different earliness identified by GDD approach. Instead, the daily thermal sum that determines the transition from one phenological phase to the next, changes. It is interesting to highlight that the shift between early-maturing and late-maturing varieties is just one week. This aspect may play a decisive role in assessing of the yield-temperature relationship and, hence, both on farmers decisions (e.g., choice of earliness) and policymakers to plan risk management policies.

RESULTS AND DISCUSSION

Results display a strong relationship between durum wheat yields and temperatures among different earliness, focusing on the each phenological phase (Table 4, more details in the Table 7, in the Appendix). More specifically, minimum temperatures that occur in the starting phase negatively affect the yields in a non-linear way, until 8-9 °C for all categories of earliness, while maximum temperatures seem to have a positive effect, until 14-15 °C, above of which the yield decrease (table 4 and table 5; more details in the table 7, in the Appendix). Yield is negatively impacted by minimum temperatures linearly occurring in growing stage (table 4, more details in the table 7, in the Appendix). According to the scientific literature, 85% of worldwide wheat cultivation is yearly affected by spring frost causing severe yield losses due to damage of micro-organelles of the cells, excessive production of reactive oxygen species (ROS) and lipid peroxidation (Hassan et al., 2021). Moreover, low temperatures in the fall season may cause yield losses until 9 percent (Tack et al., 2015). Makinen et al. (2018) found that damages due to frost negatively affect all phenological stages, even more the reproductive phase (i.e., flowering). However, focusing on the anthesis stage, our results showed contradictory evidence: minimum temperatures seem to positively affect the yields in a non-linear way, although turning points of temperatures showed that the positive relationship is true until 7-9 °C for all varieties, above of which yields decrease (table 4 and table 5; more details in the table 7, in the Appendix). It is still interesting to highlight that the effect of minimum temperatures on yields is not affected by earliness. Although the end stage lasts just a week, minimum temperatures may negatively affect the yields of early-maturing (until 10 °C) and middle-maturing varieties. Maximum temperatures occurring in starting stage positively affect the yields of all varieties in nonlinear way until 14-15 °C above of which decrease (table 5). At the same time, the adverse effects have been highlighted only in maturity for late-maturing varieties and end stages for early-maturing varieties until a certain threshold, i.e., 17 °C and 13 °C, respectively.

We also estimated the impacts of statistically significant weather coefficients among earliness and phenological stages, hence, the confidence level of temperature distributions. Results show a high confidence level, highlighting no differences among coefficients

[2] Generally, the sowing date of wheat is set on the middle of November in the Mediterranean area (Allen et al., 1998)

Table 4. Effect of temperatures on yields among phenological stages and earliness of durum wheat.

	starting			growing			anthesis			maturity			end		
	EM	MM	LM	EM	MM	LM	EM	MM	LM	EM	MM	LM	EM	MM	LM
Minimum temperature															
Maximum temperature															

Notes: EM, MM, and LM indicate the early-, middle-, and late-maturing durum wheat earliness, respectively. Red cells indicate a negative impact of temperatures on yields, blue cells a positive impact, white cells for the uncaptured relationships.

Table 5. Turning points of temperatures among phenological stages and earliness (°C).

	starting			anthesis			maturity			end		
	EM	MM	LM	EM	MM	LM	EM	MM	LM	EM	MM	LM
Minimum temperature	-8+	-8+	-9+	+8-	+9-	+7-	NS	NS	NS	-10+	NS	NS
Maximum temperature	+15-	+14-	+14-	NS	NS	NS	NS	NS	-17+	-13+	NS	NS

Notes: EM, MM, and LM, indicate the early-, middle-, and late-maturing durum wheat earliness, respectively. The values show the threshold temperatures beyond which there is a change of sign in the regression estimates (table 7, in the Appendix). NS: not significant.

Table 6. Confidence levels of temperatures distribution.

	starting		growing		anthesis		maturity		end	
	em	ml	em	ml	em	ml	em	ml	em	ml
Minimum temperature	-0.50580	-0.79056	-0.41006	0.16589	0.17650	-1.11070	-	-	-0.03887	-
Maximum temperature	1.50379	0.83624	-	-	-	-	-	-	-	-

Notes: *em* indicates the differences among coefficients of early-maturing and middle-maturing varieties divided by standard errors of baseline (i.e., middle-maturing variety); *ml* indicates the differences among coefficients of middle-maturing and late-maturing varieties divided by standard errors of baseline (i.e., middle-maturing variety).

(table 6). Therefore, the temperatures' effects on yields do not vary between earliness within each phenological phase.

It follows that early-maturing varieties are the most susceptible to changes in temperature, although the general relationship between yield and temperature is the same among earliness. Damages due to low temperatures are more likely among earliness than losses due to high temperatures. Sure enough, the vegetative stage lasts about four months, while maturity about a month and ends in just a week. Therefore, it is difficult to escape from low temperatures during starting and growing stages. Although wheat crop needs low temperature to complete vernalization processes, frost events occurring toward the end of the vegetative phase may cause severe damage such as the tiller, spike number, leaf area reduction and photosynthetic capacity, leading to a heavy yield losses (Xiao et al., 2018).

CONCLUSIONS

Given the potential impact of climate change on yields, deepening the yield-weather relationships is helping farmers cope with the weather risks. Therefore, we assess the effects of temperatures on durum wheat yields among early-maturing, middle-maturing, and late-maturing varieties. We distinguished the effects across five phenological stages (i.e., starting, growing, anthesis, maturity, and end) identified through the GDD approach, starting from the middle of November as sowing date. The levels and changes in temperatures affect durum wheat yields in several ways. More specifically, upward changes in the minimum temperatures are detrimental for to yields when they occur in the starting and growing phases, regardless of the earliness. Increases in maximum temperatures are indeed positively correlated (until a threshold of 14-15 °C) with the yields if they occur in the starting stage, whereas a negative effect is found when the event occurs at the maturity for late-maturing varieties or end stage for early-maturing varieties. Generally, the impacts of chronic heat stress, i.e., high temperatures for a longer duration, are lower than the heat shocks, i.e., extreme high temperatures for a short duration (Li et al., 2013). However, early-maturing varieties provides a better adaptation under warming conditions (Mondal et at., 2013), also because they may escape from the damages due to high temperatures by anticipating the crop cycle. Cold stress may cause morphological, physiological, biochemical, and molecular modifications in wheat. Phenotypic screening of cold-tolerant genes, pre-sowing seed treatments, and exogenous application of growth hormones may be a suitable solution tolerating severe low temperature extremes (Hassan et al., 2021). In conclusion, a better knowledge of the yield-temperature relationships, along with a deeper comprehension of the informative content of the secondary data on weather dynamics, may help both the farmers for the application of agronomic strategies, and policymakers for the planning of interventions to boost uptake in innovative crop insurance, such as the WIIs. Promoting greater comprehensibility of contracts' conditions, increasing transparency of indemnities and losses, and also improving the dissemination of risk management tools among farmers, may improve the trust, hence the adoption of subsidised insurance schemes (Giampietri et al., 2020). The main limitation of our study is the neglet of the effects of temperatures events on grain quality, although this is far beyond the scope of the analysis and will be addressed in future research. Further investigations are required to assess the effects of precipitation on yields and the choice of sowing dates to cope with climate risks.

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APPENDIX

Figure 1. Main durum wheat-producing provinces in Italy. Note: the main durum wheat-producing Italian provinces in decreasing order are: Foggia (Puglia region), Campobasso (Molise region), Palermo (Sicilia region), Ancona (Marche region), Potenza (Basilicata region), Matera (Basilicata region), Enna (Sicilia region), Macerata (Marche region), Avellino (Campania region), Catania (Sicilia region), Ferrara (Emilia-Romagna region), Caltanissetta (Sicilia region), Perugia (Umbria region), Bari (Puglia region), Viterbo (Lazio region), Bologna (Emilia-Romagna region), Ravenna (Emilia-Romagna region), Brindisi (Puglia region), Siena (Toscana region), Agrigento (Siclia region), Benevento (Campania region), Grosseto (Toscana region), Pisa (Toscara region), Chieti (Abruzzo region), Trapani (Sicilia region), Teramo (Abruzza), Roma (Lazio), Barletta-Andria-Trani (Puglia region), Rovigo (Veneto), Pesaro-Urbino (Marche region) (ISTAT, 2020).

Table 2. Descriptive statistics of daily temperatures, cumulative precipitation, and yearly yield variables for 30 main durum wheat producing provinces, 2020 year.

Province	Variable	Obs.	Mean	Median	St. dev	Min	Max
Agrigento	Maximum temperature	198	17.27042	16.475	3.656134	10.52143	31.60714
	Minimum temperature	198	10.53427	9.921429	3.269273	4.15	21.2
	Yield	198	27	27	0	27	27
Ancona	Maximum temperature	198	15.0523	14.80455	4.87341	5.245454	28.81818
	Minimum temperature	198	6.42034	5.990909	4.345694	-1.463636	16.89091
	Yield	198	45.3306	45.3306	0	45.3306	45.3306
Avellino	Maximum temperature	198	15.16203	14.54545	4.195631	4.790909	28.70909
	Minimum temperature	198	8.191552	8.095455	3.676873	-.0090909	18.63636
	Yield	198	32.81769	35	3.921524	25.80645	35
Barletta-Andria-Trani	Maximum temperature	198	16.11383	15.70625	4.502608	6.375	28.525
	Minimum temperature	198	7.62822	7.15625	3.886316	-1.1625	17.4875
	Yield	198	21.92088	22	.1421842	21.66667	22
Bari	Maximum temperature	198	15.81414	15.45833	4.549949	6.333333	29.175
	Minimum temperature	198	7.309596	6.741667	3.7425	-1.9	15.99167
	Yield	198	20.24346	20	.4374887	20	21.02564
Benevento	Maximum temperature	198	15.37965	14.735	4.230869	4.54	28.35
	Minimum temperature	198	8.102222	7.995	3.768435	-.1	18.14
	Yield	198	32.00147	31.97674	.0444387	31.97674	32.08092
Brindisi	Maximum temperature	198	16.79045	16.59	4.067458	8.61	28.66
	Minimum temperature	198	8.679343	8.05	3.772157	-.2	18.74
	Yield	198	34.8064	34.52381	.5077994	34.52381	35.71429
Bologna	Maximum temperature	198	14.48802	13.37143	5.873645	2.014286	28.45714
	Minimum temperature	198	5.333694	4.835714	4.361542	-2.635714	15.53571
	Yield	198	54.32178	55.5577	2.220902	50.35106	55.5577
Caltanissetta	Maximum temperature	198	16.8204	15.89	4.028488	9.41	32.56
	Minimum temperature	198	9.514748	8.94	3.520087	2.61	22
	Yield	198	28	28	0	28	28
Campobasso	Maximum temperature	198	15.20285	14.95455	4.480825	3.372727	26.70909
	Minimum temperature	198	8.140358	8.2	3.817845	-1.163636	17.9
	Yield	198	35.76263	36	.4265517	35	36
Catania	Maximum temperature	198	17.3101	16.73889	4.048381	9.516666	31.79445
	Minimum temperature	198	8.244501	7.669444	3.742443	.3722222	19.37222
	Yield	198	28.57143	28.57143	0	28.57143	28.57143
Chieti	Maximum temperature	198	15.16586	14.795	4.622042	3.25	26.89
	Minimum temperature	198	7.781061	7.65	3.902836	-1.2	18.08
	Yield	198	32.6417	32.84671	.3684098	31.98302	32.84671
Enna	Maximum temperature	198	16.58646	15.75455	4.356249	8.218182	32.06364
	Minimum temperature	198	8.238797	7.754546	3.665236	.4818182	20.07273
	Yield	198	30	30	0	30	30
Ferrara	Maximum temperature	198	15.09104	14	6.145688	1.991667	29.18333
	Minimum temperature	198	5.57319	5.341667	4.807333	-2.8	17.08333
	Yield	198	60.20202	64	6.824827	48	64
Foggia	Maximum temperature	198	15.9456	15.52292	4.463743	5.341667	27.81667
	Minimum temperature	198	8.216098	7.877083	3.775962	-.8	18.29583
	Yield	198	31.25	31.25	0	31.25	31.25
Grosseto	Maximum temperature	198	17.01996	16	4.174036	9.141176	27.51765
	Minimum temperature	198	7.026352	6.997059	4.34386	-1.876471	16.59412
	Yield	198	38.79645	38.84181	.0815015	38.65074	38.84181

Province	Variable	Obs.	Mean	Median	St. dev	Min	Max
	Maximum temperature	198	14.77406	14.60909	4.793149	5.263637	28.03636
Macerata	Minimum temperature	198	6.397888	6.027273	4.163119	-.9909091	16.48182
	Yield	198	42.00229	42.00229	0	42.00229	42.00229
	Maximum temperature	198	16.14141	15.80333	4.373894	6.466667	30.13333
Matera	Minimum temperature	198	7.865387	7.27	3.649867	.06	17.63333
	Yield	198	29.68525	29.68525	0	29.68525	29.68525
	Maximum temperature	198	16.95558	16.17143	3.899543	9.852381	33.84762
Palermo	Minimum temperature	198	10.14218	9.728571	3.256468	3.638095	19.40952
	Yield	198	25.99503	25.99503	0	25.99503	25.99503
	Maximum temperature	198	14.29614	13.5125	4.94103	4.515	26.96
Perugia	Minimum temperature	198	5.502298	5.37	4.366943	-2.92	15.535
	Yield	198	45.45914	44.86486	1.067896	44.86486	47.36842
	Maximum temperature	198	14.78035	14.34091	4.952188	4.390909	28.68182
Pesaro-Urbino	Minimum temperature	198	6.921442	6.786364	4.275691	-.9363636	17.32727
	Yield	198	38.00858	38.00858	0	38.00858	38.00858
	Maximum temperature	198	16.72483	15.875	4.305614	7.983333	27
Pisa	Minimum temperature	198	7.081019	7.179167	4.555321	-2.35	16.78333
	Yield	198	37.21282	40.33502	5.610488	27.1819	40.33502
	Maximum temperature	198	14.74603	14.36087	4.311705	4.573913	28.35217
Potenza	Minimum temperature	198	7.983707	7.556522	3.500149	-.1913043	18.28696
	Yield	198	27.29257	27.29257	0	27.29257	27.29257
	Maximum temperature	198	14.83678	14.03182	5.718577	2.609091	28.87273
Ravenna	Minimum temperature	198	5.954132	5.440909	4.503898	-2.563636	16.74545
	Yield	198	66.57576	68	2.55931	62	68
	Maximum temperature	198	17.05811	16.0775	3.893504	9.67	27.955
Roma	Minimum temperature	198	7.608207	7.3925	4.132565	-.35	19.59
	Yield	198	29.23737	29	.4265517	29	30
	Maximum temperature	198	14.97117	13.71818	5.981333	2.472727	28.05455
Rovigo	Minimum temperature	198	5.668916	5.363636	4.904146	-2.936364	17.71818
	Yield	198	56.23271	59.41509	5.718627	46.00845	59.41509
	Maximum temperature	198	15.97519	14.77813	4.710545	6.7125	27.15
Siena	Minimum temperature	198	5.882323	5.953125	4.678793	-3.45	16.81875
	Yield	198	37.53158	38	.8417409	36.02664	38
	Maximum temperature	198	14.60795	14.2125	4.647457	3.6875	26.6625
Teramo	Minimum temperature	198	7.074495	6.925	3.945144	-1.1	17.55
	Yield	198	39.80582	39.80582	0	39.80582	39.80582
	Maximum temperature	198	17.92341	17.12143	3.75761	10.22857	33.5
Trapani	Minimum temperature	198	10.757	10.63571	3.492239	2.428571	21.32857
	Yield	198	22.90524	23.80952	1.624959	20	23.80952
	Maximum temperature	198	16.60761	15.75	4.229603	8.413333	27.76667
Viterbo	Minimum temperature	198	7.143199	6.993333	4.106516	-.5666667	17.82
	Yield	198	38.73369	38.02031	1.281932	38.02031	41.02564

Table 7. 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	**-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
temperature	(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	**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
temperature (sq)	(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	**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
temperature	(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	**-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
temperature (sq)	(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.