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Agricultural losses related to frost events: use of the 850 hPa level temperature as an explanatory variable of the damage cost

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Abstract. The objective of this study is the analysis of damaging frost events in agriculture, by examining the relationship between the daily minimum temperature in the lower atmosphere (at an isobaric level of 850 hPa) and crop production losses. Furthermore, the study suggests a methodological approach for estimating agriculture risk due to frost events, with the aim of estimating the short-term probability and magnitude of frost-related financial losses for different levels of 850 hPa temperature. Compared with near-surface temperature forecasts, temperature forecasts at the level of 850 hPa are less influenced by varying weather conditions or by local topographical features; thus, they constitute a more consistent indicator of the forthcoming weather conditions.

The analysis of the daily monetary compensations for insured crop losses caused by weather events in Greece shows that, during the period 1999–2011, frost caused more damage to crop production than any other meteorological phenomenon. Two regions of different geographical latitudes are examined further, to account for the differences in the temperature ranges developed within their ecological environment. Using a series of linear and logistic regressions, we found that minimum temperature (at an 850 hPa level), grouped into three categories according to its magnitude, and seasonality, are significant variables when trying to explain crop damage costs, as well as to predict and quantify the likelihood and magnitude of damaging frost events.

1 Introduction

According to a recent literature review (Gobin et al., 2013), scientific interest in weather-related risks in agriculture has increased to a great extent in the last two decades, following the concern about the relationship between climate change and extreme weather and climate events, the impact of such events and the strategies to manage the associated risks (IPCC, 2012). In the climate change scenarios, crop production is expected to become more vulnerable due to the projected increase in the frequency and magnitude of weather extremes. Acknowledging the crop growth sensitivity to temperature, global increase and higher extremes of temperature represent a threat to crops (Ruiz-Ramos et al., 2011), and may cause important yield changes and production losses.

Among the weather risks, frost is responsible for serious agriculture production losses. The Food and Agriculture Organization reports that more economic losses have been caused by freezing of crops in the USA than by any other weather hazard (Snyder and de Melo-Abreu, 2005), while the ultimate cause determining cold hardiness, namely the plants' freezing tolerance, remains uncertain (Rodrigo, 2000). The extent of crop damage depends on several factors, such as the minimum temperature record, the duration of the frost event and the state of development of plants exposed to low temperatures, while frost risk also varies according to the regional topographic, morphological and geographic features. The probability and risk of damaging temperatures changes with the season of the year and, for some crops, sensitivity to damaging subzero temperatures also changes (Snyder et al., 2005). Also, greater temperature variance could increase the risk of frost damage as much

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as rising average temperatures decrease it. Overall, freezing temperatures in combination with plant growth timing determine frost damage (Eccel et al., 2009; Rigby and Porporato, 2008; Rodrigo, 2000). Thus, the relation of low temperature to the observed agricultural losses can give valuable information when trying to estimate the probability of financial losses.

Quantification of agriculture risks is very important in understanding the extent of risk and planning for its effective mitigation (Gobin et al., 2013). A literature review on weather risk in agriculture showed that most of the studies discuss the relation between climate change and the associated risks (IPCC, 2012). Several studies investigate the effects of climate change on the frequency and severity of extreme weather events like hailstorms (Berthet et al., 2011; Changnon, 2009), flooding, drought and subsequent crop yield changes (Gobin, 2012) or economic losses due to crop damage (Botzen et al., 2010; European Commission, 2009; Moonen et al., 2002; Rosenzweig et al., 2002), while some work has also been done to link climate change to monetary compensations for crop losses. Botzen et al. (2010) examine the relation between normalised agricultural hailstorm damage and a range of indicators of temperature and precipitation for the Netherlands. The authors apply long-term climate change scenarios and discuss the response of hailstorm damage due to extreme events. In Saa Requejo et al. (2011), hail damage in Spain is correlated with summer minimum temperatures. In that context, hail insurance data between 1981 and 2007 were considered to represent good estimates of hail damage intensity.

As it concerns Greece, most studies are about changes in climate elements due to the enhanced greenhouse effect. Tolika et al. (2008) assess statistical downscaling models in estimating future changes in the extreme temperature and precipitation conditions, and Giannakopoulos et al. (2011) develop future climate scenarios and explore the implications, caused by changing climate, in urban and forest areas. Results show that agriculture may be strongly affected by changing future climate conditions and indicate important changes in the number of frost nights, as well as in the length of the growing season. Nannos et al. (2013) use insurance compensations to estimate the environmental change in Greece through the economic losses caused by the crop production damage. The authors go into a statistical trend analysis of annual damage announcements and compensation data provided by the Greek Agricultural Insurance Organisation (GAIO) for the period 1986–2009, and show that in most of the cases (regions and meteorological risk types), there is a statistically significant trend.

In a few cases, future climate scenarios have been applied to perform analysis of long-term frost risk in specific crop species. Eccel et al. (2009) examine the long-term risk of spring frost to apple production in Trentino (Italy), applying a phenological model of apple flowering to a 40-year period temperature series. The authors observe a lower risk of exposure to frost at present than in the past, and probably either constant or slightly lower risk in the future. Likewise, Rigby and Porporato (2008) apply a model of phenology and daily minimum temperature, and conclude that spring frost risk to vegetation is as sensitive to increases in daily temperature variance (which increases frost risk) as to increases in the mean temperature (which decreases frost risk).

The above literature review on the relationship between weather-related variables and crop damage indicates a dearth of empirical work on the examination of the short-term frost risk as measured by the observed agricultural financial losses. Thorough examination of the relationship between meteorological variables related to frost and the observed crop damage can provide valuable tools for the quantification of frost-related risk. That said, this paper explores the relationship between the daily minimum temperature at the low levels of the atmosphere, and more precisely at the isobaric level of 850 hPa, and monetary compensations for crop damage attributed to frost. In this context, the paper suggests a methodological approach for estimating agriculture risk due to frost events, with the aim of defining damaging temperature thresholds and estimating the short-term probability and magnitude of frost-related financial losses for different ranges of 850 hPa temperature. Risk assessment, apart from the analysis of potential hazards, furthermore refers to the evaluation of the existing conditions of vulnerability, such as the physical, social, health, economic and environmental dimensions (UNISDR, 2009). However, the intention of the current study is to address only the economic risk from frost events in crop production, while the subsequent environmental or social problems are not discussed.

The use of temperature at the isobaric level of 850 hPa (T850, hereafter) as an explanatory variable of crop losses due to frost events has a number of advantages and limitations. A significant advantage is that 850 hPa is a standard level of model analysis fields, and thus there is a high availability of gridded data time series covering the entire period under examination. Also, T850 presents lower spatial variability compared to near-surface temperature. Furthermore, compared to the near-surface temperature forecast, which is more influenced by conditions such as cloudiness and phenomena related to local topographical features, the forecasted T850 constitutes a more consistent indicator of forthcoming weather conditions. On the other hand, crop damage is directly connected to local ground conditions, while the relation to temperature at the highest altitudes is certainly weaker. However, near-surface air temperature is measured at a height of between 1.25 and 2.0 m above soil level, thus representing the very local conditions and accounting for the very local agricultural damage. Furthermore, near-surface temperatures present a high local scale variability, especially in complex terrain (Scheifinger et al., 2003). Consequently, only a very dense and long-term operating network of meteorological stations could provide consistent time-series observations. However, the existing meteorological network in Greece is currently inadequate for such an analysis.

The remainder of this paper is structured as follows. Section 2 provides information about the data sources, methodological issues related to data processing, and the spatial and temporal distribution of frost events that occurred in Greece during the period 1999–2011. Section 3 presents the methods developed and the results of the statistical analyses used to investigate the relationship between the daily minimum temperature at the level of 850 hPa and the observed daily damage cost caused by frost events, as well as an estimation of the damage probability and its magnitude relative to different temperature ranges. Section 3 also presents the method and outcomes of the validation of the logistic model. Section 4 discusses the results and their significance, and Sect. 5 concludes the analysis. Finally, the Appendix includes additional methodological and statistical information, complementary to Sect. 3.

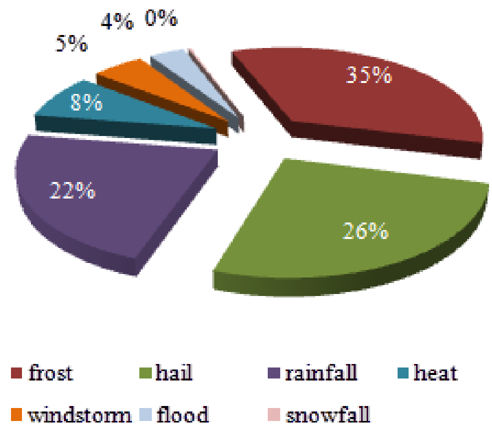

Figure 1. Distribution of insured crop losses by meteorological phenomenon (1999–2011).

2 Data and methodological issues

2.1 Sources of data

Data provided by GAIO consist of the total crop damage announcements per day and the respective monetary compensations by municipality and meteorological risk, namely hail, frost, windstorm, flood, excessive heat, and excessive or out-of-season rainfall and snowfall, for the period 1999–2011. Thus, the aggregated daily monetary compensations include the totaled insurance damage payments of the actual day the damaging event took place, at municipality level. Information on the duration of each event is not available. Therefore, in frost risk analysis, duration cannot be used as an explanatory variable of the magnitude of crop damage cost.

For the purposes of this study, the provided data have been further aggregated to account for each one of the 51 prefectures of the country still in daily analysis. At prefecture level, 116 957 announcements in total have been recorded, having an associated cost of EUR 2.8 billion in the entire examined period. Actual values have been changed to standardised values based on the year 2011, so that the impact of inflation over time is taken off. According to Botzen et al. (2010), it is a common practice to normalise historical losses for socio-economic developments before climate conditions and change impacts are analysed (Nannos et al., 2013; Barthel and Neumayer, 2012; Changnon, 2007). Specifically, standardised values of monetary compensations are calculated according to the annual GDP deflator, based on the year 2005 = 100, as reported by the Hellenic Statistical Authority (www.statistics.gr). To further readjust the values of year X costs in prices of the year 2011, the following formula was used:

$$\begin{aligned}\text{Cost}\,(2011\,\text{price}) &= \text{Cost}\,(\text{year } X \text{ price})\\ &\times \text{GDPdefl}(2011\,\text{price}) \big/ \text{GDPdefl}(\text{year } X \text{ price}).\end{aligned} \tag{1}$$

GAIO is a public insurance company that covers in a compulsory way every Greek producer, while private insurance companies cover only a small part of the total agricultural risks. The organisation operates on the basis of a number of regulations defining in detail the covered risks, the extent of the coverage, the loss evaluation and compensation method, the level of the (farmers') special insurance contribution, the various procedures, etc. (EC, 2006). With respect to compensations, GAIO covers only the direct losses of crop production, and compensates for a specified percentage of total damage rather than 100 %, due to some legitimate deductions of the level of 15 %. Damage levels less than 20 % are not paid and, thus, are not included in the insurance damage payments. The organisation covers all crop species systematically cultivated in the country. A critical parameter concerning the consistency of data provided by the Greek insurance organisation is that "insurance rule of the rural production" remained unchanged from the beginning of GAIO's operations until now (Nannos et al., 2013).

The T850 hPa data have been extracted from the ERA-Interim reanalysis database (Dee et al., 2011). ERA-Interim is the latest global atmospheric reanalysis produced by the European Centre for Medium-Range Weather Forecasts (ECMWF), with a spatial resolution of ∼ 80 km and a time resolution of 6 h. From these gridded data, points representative of northern and southern Greece have been selected, and the respective time series for these points, for the selected period, are analysed. The minimum daily T850 value of the 6 h time intervals was used in the present analysis.

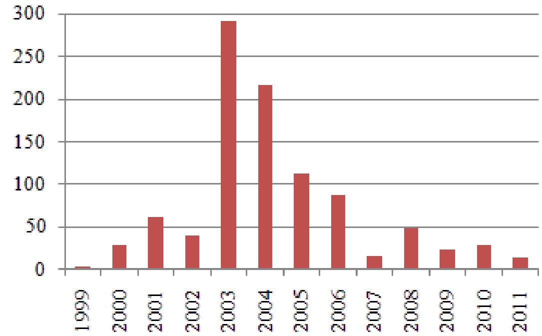

Figure 2. Annual distribution of insured crop losses due to frost events, for the period 1999–2011 (in millions of euros).

2.2 Spatial and temporal distribution of frost-related damage

Monetary compensations have been aggregated at prefecture level in order to examine the spatial and temporal distribution of the costs of frost events in Greece for the period 1999–2011, and the percentage of frost in total crop losses caused by all insured meteorological risks. The distribution of damage costs by meteorological phenomenon shows that, overall, during the period 1999–2011, frost is the most damaging one, accounting for 34.5 % of the total insured crop losses (Fig. 1), followed by hail (26.2 %) and heavy rainfall (22.4 %). The total cost of frost events is EUR 970 million. As illustrated in Fig. 2, insured crop losses due to frost vary widely between years, with damages being as low as EUR 2 million in 1999 and as high as EUR 290 million in 2003. The annual variability, however, cannot be assessed statistically, considering the short time period examined.

In the context of frost risk analysis, statistical analyses aim to examine the effect of the daily minimum temperature at an isobaric level of 850 hPa on the financial cost of crop production damage, for two different regions of the country, located in northern and southern Greece. Therefore, two regions of quite different latitudes and, consequently, temperature ranges and crop species cultivated within their ecological environment, have been examined. Furthermore, the two selected regions consist of some of the most affected prefectures, in which 70 % of total crop losses due to frost events occurred, as measured by the monetary compensations. It should be noted, as also mentioned in Sect. 2.1, that losses covered by GAIO represent approximately 85 % of total direct crop losses.

The spatial distribution of damage costs caused by frost events is depicted in Fig. 3, showing the overall damage cost that occurred to each prefecture. For presentation purposes, the costs have been grouped into four ranges. As can be seen, the selected regions in northern and southern Greece, marked with a rectangle, include some of the most affected prefectures. Specifically, the northern region is located between central and western Macedonia, and includes the prefectures

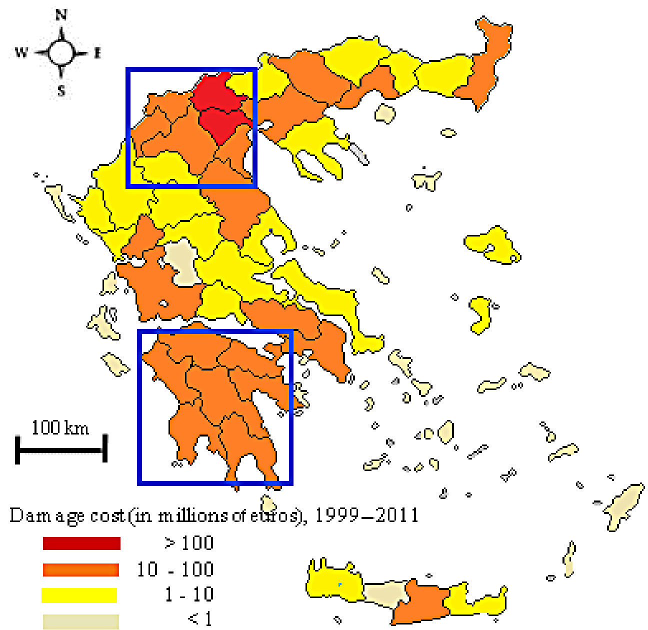

Figure 3. Insured crop losses due to frost events by prefecture (1999–2011).

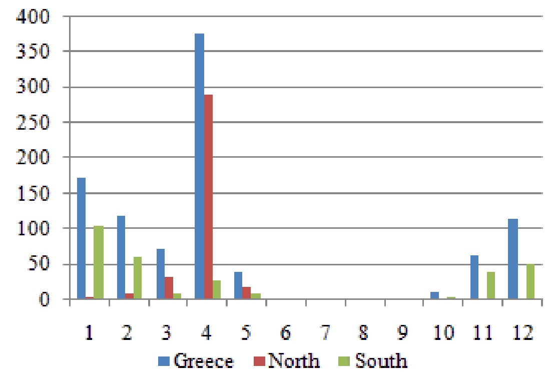

Figure 4. Monthly distribution of insured crop losses due to frost events, for the period 1999–2011 (in millions of euros).

of Pella and Imathia, which are the most affected areas of the country, as well as the prefectures of Florina, Kastoria, Kozani, Pieria and Grevena. The southern region includes the seven prefectures of Peloponnese (Corinth, Argolida, Arcadia, Messinia, Laconia, Achaia and Elia).

The monthly distribution of frost events is presented in Fig. 4, for the entire country and the two examined regions. It is obvious that, between June and September, frost events do not occur in Greece. Overall, during the period 1999–2011, the northern region, where mostly deciduous trees are cultivated, suffered mostly from spring frost events, while in the southern part, where citrus trees and olives are very common, winter was the most costly season.

Table 1. Descriptive statistics for the period 1999–2009.

Variable	Region	N	Min	Max	Mean	SD
Tmin (°C)	North	523	−18.16	14.14	−2.12	5.42
	South	534	−13.15	17.69	0.49	5.70
Cost (EUR)	North	523	1019	1.09×10^8	6.90×10^5	5.89×10^6
	South	534	1017	6.15×10^7	5.41×10^5	3.417×10^6

Table 2. Levels of minimum temperature for the two regions (°C).

tmin_c levels	North	South
tmin_1 (upper 25 %)	> (2.1)	> (4.6)
tmin_2 (middle 50 %)	(−6.2)–(2.1)	(−4.1)–(4.6)
tmin_3 (lower 25 %)	< (−6.2)	< (−4.1)

Table 3. Levels of damage severity for the two regions (in thousands of euros).

DS levels	North	South
DS1 (lower 50 %)	1.0–14.1	1.0–23.4
DS2 (middle 40 %)	14.1–329.0	23.4–674.9
DS3 (upper 10 %)	> 329.0	> 674.9

Regarding the crop species cultivated in the two regions, data on the areas cultivated (www.statistics.gr) and crop production (http://epp.eurostat.ec.europa.eu) indicate that no significant changes have occurred during the last decade. Specifically, in the northern part of the country, peach and apple trees still account for the major part of the deciduous trees cultivated (approximately 65 % and 10 %, respectively), and in Peloponnese orange trees dominate by approximately 65 %. Thus, overall, the sensitivity of the examined regions to frost events, as measured by the sensitivity of the specific crop species to the occurrence of low temperatures, has not changed. In the following statistical analyses, the type of crop species damaged by the examined frost events has not been taken into account.

3 Methods

For the following analysis, data of the 13-year period 1999–2011 have been used. More specifically, data of the 11-year period 1999–2009 were used to set the statistical models, while data of the 2-year period 2010–2011 constituted the validation sample used to evaluate the statistical outcomes. The period of 2 years allows for an acceptable validation sample size, equal to 13 % of the main statistical data size.

3.1 Measures

Table 1 presents descriptive statistics for damage costs (cost) and the respective minimum T850 (tmin, hereafter) data series for each region ("North" for the northern region and "South" for the southern region examined). The number of observations (N) refers to the amount of damaging frost events that occurred in each region at a daily level between 1999 and 2009, and is derived as the aggregation of the respective total daily damage records at prefecture level. Frost events with damage costs below EUR 1000 have been excluded from subsequent analysis. These events, which represent 17 % of the total frost events that occurred in the two regions, are considered to be extremely localised and related mostly to special near-surface weather conditions. Consequently, it is very unlikely that T850 relates to the specific frost events.

In order to investigate the relationship between tmin and costs caused by frost events in each region, tmin data have been allocated to three groups of different temperature ranges, with the aim of identifying possible temperature thresholds. Two groups represent the lowest and highest values, and specifically the lowest 25 % and the highest 25 % of the data series, while the third group includes the medium (50 %) temperature range (complementary argumentation is given in the Appendix). Thus, we created a categorical variable, named "tmin_c", which consists of three temperature levels that are further assessed for their significance in explaining the crop damage severity. The three minimum temperature levels, tmin_1, tmin_2 and tmin_3, correspond to the highest, medium and lowest temperature ranges, respectively, and specifically to the ranges presented in Table 2 for each region.

Another important parameter included in the statistical analyses is seasonality, which is considered indicative of the growth stages of crops in each region. Seasons 1, 2 and 3 correspond to winter, spring and autumn months (excluding September). Months between June and September were excluded, as the number of damaging frost events attributed to these months is of minor importance (1.3 % in total, considering both regions).

Consistent with the previous methodological approach, the estimation of the damage probability and its magnitude relative to the temperature levels required the grouping of the real damage costs into three categories that represent different damage severity (DS) levels. Specifically, the DS1, DS2 and DS3 levels refer to the lower 50 %, the middle 40 % and the upper 10 % of the cost data series, respectively

Table 4. Linear regression analysis for each region.

Variable	North[a]	South[a]
intercept	9.05*** (0.18)	9.00*** (0.25)
tmin_2vs1	−0.03 (0.20)	0.80** (0.23)
tmin_3vs2[b]	0.84*** (0.19)	1.92*** (0.22)
tmin_3vs1	0.81*** (0.24)	2.72***(0.29)
season_2vs1	2.44*** (0.19)	0.51* (0.22)
season_3vs2[b]	−2.29*** (0.27)	0.13 (0.28)
season_3vs1	0.15 (0.25)	0.64* (0.28)
Adj. R^2	0.25	0.16
F value	43.22***	26.84***

[a] Damage cost is the dependent variable. Values are unstandardised regression coefficients, with standard errors in parentheses. [b] The beta coefficients for these variables are derived when repeating the analysis to include the omitted categories. $+p < 0.10$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 5. Probabilities of cost occurring for each level of temperature.

	Probability of damage cost occurring[a]	
	North	South
All seasons[b]		
tmin_1	0.08*** (0.01)	0.10*** (0.01)
tmin_2	0.26*** (0.02)	0.23*** (0.01)
tmin_3	0.62*** (0.04)	0.63*** (0.04)
Winter		
tmin_1	0.17*** (0.02)	0.09*** (0.02)
tmin_2	0.31*** (0.02)	0.23*** (0.02)
tmin_3	0.65*** (0.04)	0.68*** (0.04)
Spring		
tmin_1	0.06*** (0.01)	0.11*** (0.01)
tmin_2	0.25*** (0.03)	0.25*** (0.02)
tmin_3	0.73*** (0.09)	0.38*** (0.10)
Autumn		
tmin_1	0.05*** (0.01)	0.07*** (0.01)
tmin_2	0.24*** (0.04)	0.20*** (0.03)
tmin_3	0.89*** (0.10)	0.86*** (0.13)

[a] Damage severity level (dichotomous DSi) is the dependent categorical variable. Standard errors in parentheses. The probability of no cost occurring equals 1 − probability of cost occurring. [b] Autumn, winter and spring. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

(complementary argumentation is given in the Appendix). The produced ranges of damage costs for the two regions are shown in Table 3.

3.2 Analyses

To examine the relationship between tmin_c and cost, ordinary least squares (OLS) regression analysis was performed. Two models were assessed, one for each region. Prior to the analysis, we transformed the dependent variable (cost) to its natural logarithm to normalise its distribution. Temperature levels were entered into the regression by means of two dummy variables, namely tmin_2 and tmin_3 (tmin_1 was set as the baseline group). To evaluate the effects of seasonality, two additional dummy variables, namely season_2 and season_3 (season_1 was set as the baseline group), were also entered into the regression. To assess possible variations between the second and third categories for both the tmin_c and season variables, regressions were re-run with different groups as baselines. In these repetitions, the F and R squared values as well as the significance of the variable coefficients remained unchanged. Table 4 shows the output of the regression analysis for each region.

F values for both models (North and South) are significant at the 0.1 % level, indicating a very good fit of the data. The adjusted R square of the two models is 25 and 16 %, respectively, showing, thus, higher explanatory power in the model corresponding to the northern region. To assess multicollinearity, we computed the variance inflation factor (VIF) scores. All values were well below the accepted cut-off of 10 (Hair et al., 2006), ranging from 1.14 to 1.71.

The coefficients of the dummy variable tmin_c inform us about how (direction) and how much (significance) the damage cost is expected to change when the temperature changes from one level to the other. Accordingly, the two models, North and South, indicate significantly different effects on damage cost between low levels (tmin_3) and medium levels (tmin_2), as well as between low levels (tmin_3) and high levels (temp_1) of temperature. Differences between medium and high levels of temperature are statistically significant only in the case of the southern region. Concerning the season variable, the analyses show that, overall, seasonality affects damage costs. Specifically, for both regions, two of the three pairs of groups produce different effects on cost at a statistically significant level.

We furthermore propose a methodological approach of risk analysis, with the aim of predicting (a) the likelihood that a frost event will occur at each temperature level, and (b) the probability that a certain level of damage cost will occur at each temperature level.

To produce the probability of a frost event occurring, we used a dichotomous variable DSi as the dependent variable. DSi takes values of 0 (no damage cost was recorded on a certain day) or 1 (any cost was recorded). The categorical tmin_c was used as the explanatory variable, based on the temperature thresholds that were derived from the grouping of tmin when only days with damage cost were included (Table 2). Thus, tmin_c levels represent the same temperature ranges as the ones presented in Table 2, but with different proportions. Specifically, when all days of all the examined seasons (winter, spring, autumn) are included, the tmin_1, tmin_2 and tmin_3 levels correspond to the upper 59 %, the medium 34 % and the lower 7 % of tmin data in the case of the northern region, and to the upper 50 %, the medium 42 % and the lower 8 % of tmin data in the case of the southern region.

For the initial analysis, seasonality was controlled with the inclusion of the associated categorical variable. Due to the nature of the dependent variable, two logit regressions (one for each region) were performed. To investigate variations between the different seasons further, we run a separate logit regression for each season and region (additional statistical information is given in the Appendix, Table A1).

To obtain the predicted probabilities of a cost occurring at each level of temperature, we used a margin analysis after performing each logit regression. The outputs for these analyses are presented in Table 5.

After producing the probabilities of a damage cost occurring (i.e. the presence of a damage cost), the next set of analyses aims to predict the probability of a certain level of damage cost occurring (i.e. magnitude of damage cost) at each temperature level. Note that days with no damage cost occurrence were eliminated from the analysis. Thus, the produced probabilities refer to the days with damage costs.

For the specific analysis, DS was used as the dependent variable. Consistent with the previous analysis, we performed an overall analysis by controlling seasonality while also running a separate analysis for each season. DS consists of three groups that indicate low, medium and high levels of damage cost. Due to the ordinal nature of the variable, a generalised ordered logit regression methodology (using maximum likelihood estimation) was employed. The advantage of this method is that it relaxes the proportional odds assumption underlying ordered logit regression, according to which the relationship between each pair of outcome groups is the same (additional statistical information is given in the Appendix, Table A2).

To obtain the predicted probabilities of a certain level of damage cost occurring at each level of temperature, we used a margin analysis after performing each generalised ordered logit regression. The outputs for these analyses are presented in Table 6.

To illustrate how the output of Table 6 is interpreted, the first row of the table shows the probabilities of different levels of DS occurring at each temperature level. Therefore, for the northern region, if on a certain day the temperature falls into the first category (i.e. high temperature), then the probability of low DS (DS1) occurring is 57 %, the probability of medium DS (DS2) occurring is 35 %, and the probability of high DS (DS3) occurring is 8 % (the sum of the probabilities is 100 %).

3.3 Validation of the logistic model

Validation of the logistic model developed for predicting probabilities of a cost occurring (Table 5) has been performed, setting as a validation sample the data of the period 2010–2011.

The results of the logistic regression analysis, presented in Sect. 3.2, have been used to establish the dichotomy of risk/no risk of frost events occurring. It was considered that probabilities under 50 % correspond to events for which no cost is expected, while probabilities over 50 % permit a warning for a damaging frost event (López et al., 2007). Based on this criterion and the results shown in Table 5, a warning for possible crop damage in the cases of high and medium tmin levels (tmin_1 and tmin_2) has been considered not applicable, due to the particularly low estimated probabilities of events with costs occurring for both regions. Regarding the tmin_3 level, the logistic model predicts 61 and 63 % probabilities of damaging events in the north and south, respectively, which permit a warning when the expected temperature at the 850 hPa level is lower than the tmin_3 threshold.

Table 6. Probabilities of different damage severity (DS) levels occurring for each level of temperature.

North[a]	All seasons[b]	DS1	DS2	DS3
	tmin_1	0.57*** (0.04)	0.35*** (0.04)	0.08*** (0.02)
	tmin_2	0.49*** (0.02)	0.42*** (0.02)	0.09*** (0.01)
	tmin_3	0.41*** (0.04)	0.48*** (0.04)	0.11*** (0.02)
	winter			
	tmin_1	0.76*** (0.04)	0.23*** (0.05)	0.01 (0.01)
	tmin_2	0.61*** (0.03)	0.37*** (0.03)	0.02* (0.01)
	tmin_3	0.44*** (0.04)	0.52*** (0.04)	0.04* (0.02)
	spring			
	tmin_1	0.17*** (0.05)	0.50*** (0.07)	0.33*** (0.06)
	tmin_2	0.23*** (0.04)	0.43*** (0.05)	0.34*** (0.04)
	tmin_3	0.30*** (0.09)	0.34** (0.10)	0.36*** (0.09)
	autumn			
	tmin_1	0.65*** (0.08)	0.34*** (0.08)	0.01 (0.01)
	tmin_2	0.55*** (0.07)	0.42*** (0.07)	0.03 (0.03)
	tmin_3	0.45** (0.13)	0.32* (0.14)	0.23 (0.13)
South[a]	All seasons[b]			
	tmin_1	0.74*** (0.03)	0.25*** (0.03)	0.01* (0.01)
	tmin_2	0.50*** (0.02)	0.43*** (0.02)	0.07*** (0.01)
	tmin_3	0.27*** (0.04)	0.44*** (0.04)	0.29*** (0.04)
	winter			
	tmin_1	0.87*** (0.04)	0.12** (0.04)	0.01 (0.01)
	tmin_2	0.57*** (0.04)	0.37*** (0.04)	0.06** (0.02)
	tmin_3	0.22*** (0.04)	0.54*** (0.04)	0.24*** (0.04)
	spring			
	tmin_1	0.61***(0.05)	0.37***(0.05)	0.02 (0.01)
	tmin_2	0.53*** (0.04)	0.40*** (0.04)	0.07** (0.02)
	tmin_3	0.45*** (0.09)	0.29** (0.11)	0.26* (0.11)
	autumn			
	tmin_1	0.70*** (0.07)	0.29*** (0.07)	0.01 (0.01)
	tmin_2	0.44*** (0.08)	0.46*** (0.08)	0.10* (0.05)
	tmin_3	0.21* (0.11)	0.23 (0.14)	0.56*** (0.16)

[a] Damage severity level is the dependent categorical variable. Standard errors in parentheses.
[b] Autumn, winter and spring. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

4 Discussion

The first objective of the present study was to answer the question of whether and how the level of the minimum temperature at the isobaric level of 850 hPa relates to crop production damage. This is a critical issue before moving forward, because it defines the importance of all the next steps of the analysis. According to the results of the regression analyses (Table 4), the level of tmin (minimum T850) explains a considerable part of the produced damage cost, in both the northern and southern regions under examination. Therefore, T850 is proven to be a parameter that can be directly linked to the development and magnitude of damaging frost events. This is a promising result, considering the fact that T850 is less influenced by cloudiness and local topography and morphology compared to the near-surface temperature, and its forecast is highly reliable. Consequently, it could be used in the context of an information tool, with the aim of providing warnings for frost risk with potential crop damage.

A more analytical examination of the regression results (Table 4) shows that the different tmin levels are associated with quite different magnitudes of damage costs. Especially when moving from the middle or high ranges of tmin (tmin_2 and tmin_1) to the lowest one (tmin_3), the associated cost is expected to be significantly higher in both regions examined (northern and southern). For the northern region, it seems that the critical threshold is only one, and in particular the low tmin level, while for the southern region, the cost is differently affected by all three tmin levels. The season effect is also significant, but divergence is observed between the two regions. In the north, results indicate significantly increased damage costs when comparing spring (season_2) with winter (season_1) and autumn (season_3). The outcomes imply that spring frost events may damage crops considerably, depending apparently on the growth stage of the plants at this time of the year. Indeed, as the Food and Agriculture Organization reports, deciduous fruit trees, which are the most common plants cultivated in the northern region, are more sensitive in spring and autumn (Snyder and de Melo-Abreu, 2005). Likewise, Rodrigo (2000) reports that in temperate climates, losses due to frosts during bloom are more important than those due to low winter temperatures. For the southern region, though, results are not statistically significant with respect to the effect of spring versus the effect of autumn, thus spring is not by definition expected to be associated with higher costs. According to Rodrigo (2000), freezing injuries to fruit trees can be associated with low temperatures prior to dormancy in the autumn, in midwinter during dormancy, or during and after budbreak in the spring. According to the regression results, in the period 1999–2009, spring and autumn in the southern region exhibited approximately the same rate of financial losses and similar rates of daily losses due to crop damage during frost events (EUR 41 and 45 million for spring and autumn frost events, respectively), which partly explains the regression analysis outcomes.

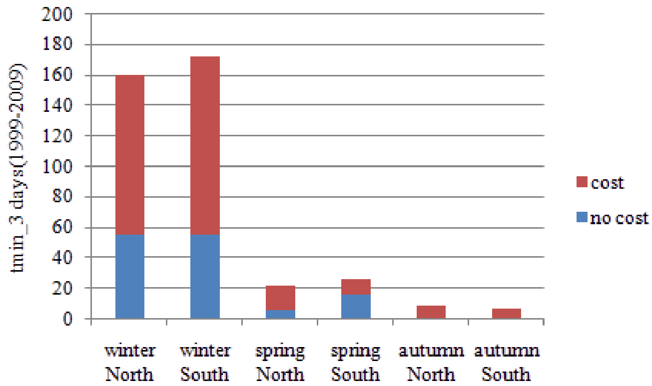

Figure 5. Number of days with low tmin observations (tmin_3 level) by region, associated or not with crop damage (1999–2009).

Concerning the predicted probabilities of a cost occurring at each level of tmin, the analyses show that, as tmin falls from higher to lower levels, the likelihood of crop damage occurring increases significantly, regardless of the season (Table 5). Predicted probabilities of a damage cost occurring, taking seasonality into account, are differentiated slightly between north and south (Table 5), with the exception of springtime low temperature records, for which the probability of damages is expected to be much higher for the north. In the low tmin level, autumn involves the greatest risk in both regions compared to the other seasons; that is, the probability of any cost occurring is high, specifically when tmin falls to the tmin_3 level. This outcome depends of course on the selected tmin thresholds (Table 2) and the frequency of tmin_3 observations recorded in the season examined. It is interesting to observe in Fig. 5 the number of days that correspond to the tmin_3 level, for the period 1999–2009, and associated or not with crop damage (cost or no cost). More specifically, the number of days with tmin_3 observations is very low during autumn in both regions, and almost all of them (8 out of 9 days in the north, and 6 out 7 days in the south) are associated with the occurrence of crop damage. This analogy is obviously responsible for the high probability of any cost occurring in the low tmin level. Accordingly, the respective proportions for spring and winter lead to lower or much lower probabilities of crop damage.

The damage severity (DS) of frost events, as measured by the expected cost due to crop losses, is shown in Table 6. Depending on the tmin level, winter exhibits probabilities high enough to be considered warnings only for low and medium DS. Spring in the north also gives noticeable probabilities of high DS (DS3), which, though, lie between 30 and 36 %, according to the tmin level. However, medium as well as low tmin are both expected to associate mostly with medium DS. In the south, during spring, low DS is more likely to occur in the case of a frost event. The severity of a damaging frost event during autumn is expected to be considerably high in the south only for low tmin records, with a

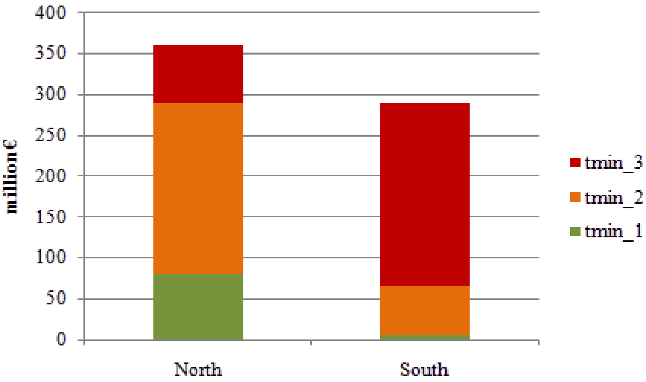

Figure 6. Distribution of frost-related insured crop losses by tmin level (1999–2009).

probability of over 50 %. Significant damage is not expected in the case of high tmin. However, crop damage has occurred even when T850 is high. Actually, 25 % of frost events in both regions relate to high tmin values and correspond to 13 % of total insured crop losses (Fig. 6), which confirms that T850 is not always representative of the near-surface weather conditions, where radiative cooling and, subsequently, temperature inversions (i.e. temperature increases with height) may occur.

The evaluation of the logistic model – which provides predictions of the probability of the occurrence of a cost-damaging event – has been performed, as already mentioned, only for events belonging to the low tmin_3 level. Overall, in the period 2010–2011, 140 daily frost events with crop damages amounting to EUR 26.8 million occurred in the two regions examined, 22 of which relate to the low tmin threshold (tmin_3). Indeed, 65 events with a total cost of EUR 24.4 million occurred in the south, and 75 events with a cost of EUR 2.4 million in the north. As the events in the north mainly had low daily costs during the period 2010–2011, the validation will be restricted in the south and for the events with daily costs exceeding EUR 100 000.

During the validation period, 16 events with costs exceeding EUR 100 000 occurred in the southern region, 6 of which (accounting for 37 % of the cases) were in the tmin_3 category. Although only for 37 % of the events would a warning have been issued, these events accounted for 79 % of the total costs in the south for the examined period. The aforementioned percentages show that the tmin_3 threshold could be used at least as a threshold for issuing successful warnings for the high damaging events.

Focusing again on the southern region, the false alarm ratio (FAR), which represents the fraction of the predicted events that did not actually occur, has been calculated for the same validation period and equals 0.44. This FAR value is quite high, but it should be viewed under the light of the cost of mitigation strategies, which is a factor not considered in our study.

5 Concluding remarks

In this study, analysis of the agricultural losses of the period 1999–2011 has been performed. It was found that frost is the most damaging weather-related phenomenon, accounting for 34.5 % of the total insured crop losses in Greece. This finding motivated the investigation of the relationship between the daily minimum temperature at the 850 hPa level (tmin) and the observed damage cost caused by frost events. Results have been found to be statistically significant, indicating that the level of tmin explains a considerable part of the produced damage cost. Moreover, the statistical analysis aimed at providing estimates of the damage probability and its magnitude relative to different temperature ranges. Overall, results are better for the northern region. Specifically, regression analysis of the relationship between tmin and cost resulted in a higher explanatory power (the adjusted R square is 25 %), the effect of tmin levels indicated one specific temperature threshold (the low tmin level) under which the cost is significantly higher, and spring was also clearly linked to higher damage cost. Surprisingly, autumn has been found to involve the greatest risk in both regions compared to the other seasons concerning the probability of any cost occurring when low tmin records occur. This outcome, however, relates to the selected tmin thresholds and the low frequency of days with low tmin observations, most of which presented damaging frost events.

Finally, the logistic model that provides predictions for the probability of the occurrence of a cost-damaging event was evaluated on an independent 2-year validation sample only for events belonging to the low tmin_3 level. The analysis of the cost-damaging events in the southern region showed that if the tmin_3 threshold was used to issue a warning, there would have been a successful alert for the events that caused 79 % of the total damages in the validation period.

The outcomes of the statistical analyses provide valuable information regarding the qualitative and quantitative characteristics of frost-related risk in agriculture that may contribute to the research into agriculture risk assessment and management. To a large extent, the potential for frost damage depends on local conditions, and thus it is difficult to assess, due to the uncertainty included in weather forecasts. It is in the future plans of the authors to assess the outcomes of the present analysis further, while frost events and agriculture damage will keep on being systematically observed as part of the authors' research into weather-related risks in Greece and the subsequent socio-economic impacts (Papagiannaki et al., 2013).

Appendix A: Sensitivity analysis and supplementary output

To enhance the robustness of our methodology and to check for methodological consistency, statistical analyses were also performed for different groupings of tmin, setting in all cases equal percentages for defining the lower and upper tmin_c levels (from 20 to 35 %). In all cases, the analyses produced consistent results.

Accordingly, the analyses have also been performed for a different grouping of damage severity, where the DS1, DS2 and DS3 levels correspond to the lower 50 %, the middle 30 % and the upper 20 % of the data series. As expected, when the DS3 level included the upper 20 % instead of the 10 % of the cost data, results of the analyses for both regions showed a consistent increase in DS3 probabilities, as well as a respective decrease in DS2 probabilities. The direction of these changes is in line with the main findings of the study, and further supports their validity.

Logit regressions fit statistics.

Table A1 provides fit statistics for the logit regressions. The prob > chi2 for all models is significant at the 5 % level, indicating a perfect fit of the data.

Table A2 provides fit statistics for the generalised ordered logistic models. In all models, except one, the prob > chi2 is significant at the 5 % level, indicating a perfect fit of the data.

Table A1. Fit statistics for logit regressions.

Models	*N*	LR chi2	Prob > chi2	Pseudo R2
North				
All seasons*	2676	439.96	< 0.00	0.17
Winter	993	106.85	< 0.00	0.09
Spring	1012	104.64	< 0.00	0.14
Autumn	671	64.11	< 0.00	0.15
South				
All seasons*	2676	312.92	< 0.00	0.12
Winter	993	160.39	< 0.00	0.13
Spring	1012	37.48	< 0.00	0.04
Autumn	671	37.54	< 0.00	0.08

* Autumn, winter and spring.

Table A2. Fit statistics for generalised ordered logit regressions.

Models	*N*	LR chi2	Prob > chi2	Pseudo R2
North				
All seasons*	515	27.04	< 0.00	0.03
Winter	326	15.56	< 0.00	0.03
Spring	124	1.79	0.41	0.01
Autumn	65	6.44	0.04	0.06
South				
All seasons*	528	78.83	< 0.00	0.08
Winter	285	54.36	< 0.00	0.10
Spring	170	9.23	< 0.01	0.03
Autumn	73	18.54	< 0.00	0.14

* Autumn, winter and spring.

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