ANSWERS TO THE REVIEWERS' COMMENTS

We would like to sincerely thank the two reviewers for their constructive comments that helped us to significantly improve the presentation and the overall argumentation and quality of our paper. Following all their comments and suggestions we proceeded to a thorough revision of the article. In more detail, the following changes have been made in accordance with the respective comments of the reviewers:

Reviewer 1

Specific comments

1. 'In Section 1 (Introduction), page 2, line 12: "Weather is definitely the major risk in agriculture" is not an appropriate phrase and should be a changed to a something like "Extreme weather or adverse weather conditions…".'

The specific sentence has been rephrased according to the suggestion.

2. 'In Section 2 (Data and methodological issues), page 6, line 6: The term "daily announcement" should be more clarified i.e. includes the totaled insurance damage payments of the day? or all the individuals insurance records corresponding to each particular day?'

Data provided by GAIO actually consist of the total crop damage announcements and the respective monetary compensations by municipality and meteorological risk, aggregated at daily level for the period 1999 to 2011. To make it clear, we rephrased according to the suggestion. Relevant clarifications have been made where needed in the rest of the text.

3. 'In Section 2 (Data and methodological issues), page 7, line 2: The damage insurance level payments do not represent the total 100% of the crop damage. There are some "legitimate deductions" of the level of 15%. Also, damage level less than 20% is not paid and thus in not included in the insurance damage payments. This information should be included in this paragraph and if elsewhere needed in the text explaining that economic amount data examined do not represent the complete (100%) crop damage.'

We rephrased according to the suggestion. Relevant clarifications have been made where needed in the rest of the text.

4. 'In Section 2 (Data and methodological issues), page 7, line 10: As the text in the following is everywhere referred to 850 hPa minimum temperature, it should be specified here if the minimum daily temperature value of the 6-hour time intervals was used in this analysis.'

The minimum daily T850 value of the 6-hour time intervals was used in the present analysis. This information has been also inserted into the text following the relevant suggestion.

5. 'In Section 3 (Methods) page 9, line 5: The number of observations (N) as it referred to "daily damage announcements" should be clarified if they are total daily damage or individual damage records of any particular day.'

The number of observations (N) refers to the amount of damaging frost events that occurred in each region at daily level between 1999 and 2009, and derives as the aggregation of the respective total daily damage records at prefecture level. This information has been inserted into the text following the relevant suggestion.

6. 'In Section 4 (Discussion), page 14, lines 4-5: Given the smallest number of damage announcements and the smallest damage cost occurring in Autumn in comparison to other seasons, it is an interesting result that the probability of damage to occur is highest for Autumn to both North and South areas (Table 5). Is it a result primary related to temperatures or to frost vulnerability of exposed crop types in Autumn? any comment or explanation is welcome here.'

Indeed, autumn has been found with the highest probabilities for a cost to occur when tmin is low (tmin_3 level). Also, results of the regression analysis are not statistically significant in what concerns the difference in the effects of spring and autumn on the damage cost attributed to frost events in the south region examined. A more careful inspection of background data, following the reviewer's suggestions, came up with explanatory comments that are believed to clarify the analyses outcomes. More specifically, in the period 1999-2009, spring and autumn in the south region exhibited approximately the same rate of financial losses due to crop damages during frost events (41 and 45 million euros for spring and autumn frost events, respectively), which partly explains the regression analysis outcomes. Regarding the high probabilities for any cost to occur in the low tmin level, autumn involves the greatest risk in both regions compared to the other seasons. This outcome depends of course on the selected tmin thresholds and the frequency of tmin_3 observations recorded in autumn. It is interesting to observe in the number of days that correspond to tmin_3 level, for the period 1999-2009, and associate or not with crop damages (new Figure 5). 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) associate with the occurrence of crop damages. This analogy is obviously responsible for the high probability of any cost to occur in the low tmin level. Accordingly, the respective proportions for spring and winter lead to lower or much lower probabilities for crop damages.

It should be noticed that <u>the entire Section 4 (Discussion) has been thoroughly revised</u>, following the suggestions of both reviewers and especially due to the addition of the validation process of the logistic model on a 2-year validation sample.

7. 'In Section 5 (Concluding remarks), page 15, line 11-13: Following the above, the conclusion here should be also completed with some small comment explaining the statistical high risk of Autumn frost damage costs, given the smallest overall frost damage events and cost exhibited in Autumn.'

Concluding remarks have been revised accordingly. More comments, explaining analytically the statistical high risk of autumn, are included in Section 4 (Discussion).

<u>Technical corrections</u>

1. 'In Section 4 (Discussion), page 14, lines 8, 12: Where it is referred temperature units "C", should be corrected to "oC".'

Corrections have been made according to the suggestions.

2. 'Same corrections as above, page 14, lines 23, 25.'

Corrections have been made according to the suggestions.

3. 'In Figure 2, the y axis scaling might be better readable if would be changed to million Euros, instead of Euros.'

Corrections have been made according to the suggestions.

Reviewer 2

General comments

'The paper focuses on analysing the risk of frost events and their relationship with agricultural losses, studying the relationship between the daily minimum temperature at the low levels of the atmosphere and more precisely at the pressure level of 850 hPa, and monetary compensations for crop damages attributed to frost. I would like to know why the authors have not used the surface temperature; topographic factors and variations in the boundary layer can mean that the data are not representative. The authors should include a more complete logistical model, in which the explained variance increases, validated using an independent sample. I would therefore recommend that a series of changes be made to the paper.'

The reviewer's concern regarding the variables explored and the magnitude of the explained variance is acknowledged. We hope that the following reply to the comments will provide appropriate explanation for the selection of the specific variables (T850 and seasonality).

According to the past studies, the extent of freezing is determined by minimum temperature, crop species and the state of development of plants. As mentioned in the introduction, freezing temperatures in combination with plants growth timing determine frost damage (Eccel et al., 2009; Rigby and Porporato, 2008; Rodrigo, 2000). Temperature at the pressure level of 850 hPa has the advantage of being a more consistent indicator of forthcoming weather conditions compared to the near-surface temperature, which is more influenced by conditions such as cloudiness and phenomena related with local topographical features. Also, 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. Thus, if T850 is proved to be a parameter that can be directly linked to the development and magnitude of frost damaging events, its highly reliable forecast can be used for the development of practical and useful warning tools.

Crop sensitivity of course is strongly affected by ground local conditions, while the relation with temperature in higher altitudes is certainly weaker. However, due to the fact that near-surface temperature represents the very local conditions and accounts for the very local agricultural damages, a very dense and long-time operating network of meteorological stations is required to obtain consistent time-series observations. The existing meteorological network in Greece is currently inadequate for such an analysis.

In what concerns the plants growth stage, it is partly captured by the inclusion of seasonality in our analysis, since the phenology of plants is closely related with the yearly cycle of plants growth. With regards to the species of crops, we utilized available information concerning the crop species cultivated in the two regions under examination. According to the official statistics, there have not occurred any significant changes in the areas cultivated or in crop production by species during the last decade, 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. Data on the type of crop species damaged by the examined frost events were not available and thus have not been taken into account in the statistical analyses. Other variables affecting frost risk may include precipitation (more details can be found in the context of the reviewer's 2nd specific comment) and snowfall. The inclusion of such variables could increase the variance explained by the model. Nevertheless, previous research consider these variables as having limited significance regarding the extent of plants injury compared to minimum temperature and growth stage. In addition, forecasting of such variables is complicated and highly uncertain.

The reviewer's suggestion regarding the validation of the logistic model is considered significant for the improvement of the methodology. Therefore, we proceeded to a thorough revision of the entire methodology taking into account the validation of the model that calculates the probability for any cost to occur in the various levels of minimum temperature (more details can be found in the context of the reviewer's 3rd specific comment).

Specific comments

1. 'In Section 1 (Introduction): The authors refer to Climate Change and agricultural risks, but do not go on to analyse this in the paper. I think that the introduction could be significantly improved with a more meticulous line of argument.'

Introduction has been enriched with the inclusion of some additional information about the relationship between climate change and weather related risks and with additional relevant references (Eccel et al., 2008; Ruiz-Ramos et al., 2011). The relation of weather extremes with frost risk in the context of our analysis has not been further discussed since the employed methodology does not go beyond the short-term analysis, while the annual data set is considered too short for observing trends on meteorological extremes.

2. 'In Section 2: The annual variability has not been analysed, probably because the annual data set is short. Is it possible that other meteorological factors such as precipitation may affect the sensitivity of crops, and that this causes changes in the damage caused by frost events? Should other meteorological fields be analysed that may include synergies, like precipitation?'

Indeed, as it is mentioned in Section 2.2, the annual variability cannot be statistically assessed, considering the short time period examined. As far as the variables affecting crops sensitivity are concerned, precipitation may be one of them. However, to our knowledge, research has not yet produced valid results concerning the relation between precipitation and frost risk. According to the existing literature, frost risk is determined by the daily minimum temperature and the plants growth stage (Eccel et al., 2009;

Rigby and Porporato, 2008; Rodrigo, 2000). The inclusion of seasonality in our analysis captures partly the effect of the growth stage, since the phenology of plants is closely related with the yearly cycle of plants growth. According to Rodrigo (2000), precipitation is not expected to be determinant, but rather indirectly related, in some species, to the hardiness of flower buds, by affecting their moisture content. The author, however, explains that the effect of the moisture content is not yet determined and may depend on the species or even other factors. Thus, inclusion of precipitation in the analysis could produce confusing results without the inclusion of other factors, such as crop species, especially since its effect on frost risk is questionable.

Furthermore, precipitation data at such a temporal analysis (long time-series daily data) or spatial level (they should cover all local precipitation events, including solid precipitation which is seldom recorded, that occurred in the broad regions examined) do not exist. Such an analysis could be representative only for particularly small geographical areas, covered by local meteorological stations, which is though outside the current study's scope.

Finally, the forecast of precipitation is highly uncertain compared to temperature and particularly T850, which is less influenced by cloudiness and local topography and morphology compared to the near-surface temperature and its forecast is highly reliable.

3. 'In Section 3 (Methods): I consider that the data treatment and conclusions are slightly lacking in content, and should be analysed in greater detail. I would like to see a contingency table in which the forecasting equations are applied to an independent sample. What are the FAR or POD of the logistic models?'

Following this very important comment regarding the validation of the logistic model we proceeded to a substantial revision of the entire methodology, as well as of the discussion of results and conclusions. The methodological revision relates to the development of a validation process which entailed changes in the entire document. Specifically:

1. The 1999-2011 time-series data have been divided into 2 data sets, for the statistical analysis and the validation process respectively. Therefore, 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.
2. Sections 3.1 (Measures) and 3.2 (Analyses) concern the statistical data set (1999-2009), while Section 3.3 (Validation) has been added to present the validation methodology (including the FAR score).
3. All tables in Section 3 (Methods), Section 4 (Discussion) Section 5 and (Conclusions) have been accordingly revised. References have been also updated (addition of Lopez et al. 2007)

Note that regression results have not changed significantly compared to the 1st submission's results that came up from the analyses of the period 1999-2011. Information on data treatment and discussion of results has also been revised and considerably improved.

In what concerns the validation methodology, the results of the logistic regression analysis for the period 1999-2009, presented in section 3.2, have been used to establish the dichotomy of risk/no risk of frost events to occur. It was considered that probabilities under 50% correspond to events for which no cost is expected, while probabilities over 50% permit for a warning of frost damaging event (López et al., 2007). Based on this criterion and the results shown in Table 5, warning for possible crop damages is applicable only when T850 is forecasted to be lower than the tmin_3 threshold (low tmin level). This applies for both regions. However, as the events in the north were mainly low daily cost during the period 2010-2011, the validation was restricted in the south and for the events with daily cost exceeding 100,000 euros. During the validation period 16 events with cost exceeding 100,000 euros occurred in the south region, 6 out of which (accounting for 37%) of the cases were in the tmin_3 category. Although only for the 37% of the events there would have been issued a warning, these events accounted for the 79% of the total cost 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 in the south region, the False Alarm Ratio (FAR), that represents the fraction of the predicted events that did not actually occur, has been calculated for the same validation period and equals 0.47. 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.

4. 'The graphic quality of the figures has to be improved to adapt them to the required level for a scientific article.'

All figures have been revised according the suggestions. Two additional figures (fig. 5 and fig.6) have been included.

The revised paper is presented in the following section

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

Papagiannaki K.[1], Lagouvardos K.[1], Kotroni V.[1], and Papagiannakis G.[2]

[1]Institute for Environmental Research and Sustainable Development

National Observatory of Athens, Athens, Greece

[2]Athens University of Economics and Business, Athens, Greece

Abstract

The objective of this study is the analysis of frost damaging events in agriculture, by examining the relationship between the daily minimum temperature at the lower atmosphere (at the pressure 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 to estimate 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 forecast at the level of 850 hPa is less influenced by varying weather conditions, as well as by local topographical features, thus it constitutes 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, during the period 1999-2011, shows that frost is the major meteorological phenomenon with adverse effects on crop productivity in the largest

---

[1] *Correspondence to*: K. Papagiannaki

katpap@noa.gr

part of the country. Two regions of different geographical latitude are further examined, 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 850 hPa level), grouped in 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 frost damaging events.

1. Introduction

According to a recent literature review (Gobin et al., 2013), scientific interest for weather-related risks in agriculture has increased to a great extent in the last two decades, following the concern on 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, R. L. and de Melo-Abreu, 2005), while the ultimate causes determining cold hardiness, namely the plants freezing tolerance, remain 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, R. L. et al., 2005). Also, greater temperature variance could increase the risk of frost damage as much as rising average temperatures decrease it. Overall, freezing temperatures in combination with plants 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). 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 damages (Botzen et al., 2010; European Commission, 2009; Moonen et al., 2002; Rosenzweig et al., 2002), while some work has been also done to link climate change with monetary compensations for crop losses. Botzen et al. (2010) examine the relation between normalized 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 damages due to extreme events. In Saa Requejo et al. (2011), hail damages in Spain are 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 of 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 damages. The authors go into a statistical trend analysis of annual damages announcements and compensation data provided by the Greek Agricultural Insurance Organization (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 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 lower risk of exposure to frost at present than in the past and probably either constant or a slightly lower risk in 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 relation between weather-related variables and crop damages 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 relation between meteorological variables related to frost and the observed crop damages can provide valuable tools for the quantification of frost-related risk. That said, this paper explores the relation between the daily minimum temperature at the low levels of the atmosphere, and more precisely at the pressure level of 850 hPa, and monetary compensations for crop damages attributed to frost. In this context, the paper suggests a methodological approach for estimating agriculture risk due to frost events with the aim to define damaging temperature thresholds and to estimate the short-term probability and magnitude of frost-related financial losses for different ranges of 850hPa temperature. Risk assessment, apart from the analysis of potential hazards, further 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 pressure level of 850 hPa (T850, hereafter) as an explanatory variable of crop losses due to frost events has a number of advantages and limitations. 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 with local topographical features, forecasted T850 constitutes a more consistent indicator of forthcoming weather conditions. On the other hand, crop damages are directly connected with ground local conditions, while the relation with temperature in 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 damages. 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-time 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 850hPa and the observed daily damage cost caused by frost events, as well as an estimation of the damage probability and its magnitude relatively 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 Section

5 concludes the analysis. Finally, Appendix includes additional methodological and statistical information, complementary to Section 3.

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, excessive or out of season rainfall and snowfall, for the period 1999 to 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 at daily analysis. At prefecture level, 116,957 announcements in total have been recorded, having an associated cost of 2.8 billion euros in the entire examined period. Actual values have been changed to standardized values based on 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 normalize historical losses for socio-economic developments before climate conditions and change impacts are analyzed (Nannos et al., 2013; Barthel and Neumayer, 2012; Changnon, 2007). Specifically, standardized values of monetary compensations are calculated according to the annual GDP deflator, based on 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 year 2011, the following formula was used:

$$\mathrm{Cost}(2011\ \mathrm{price}) = \mathrm{Cost}(\mathrm{yearX\ price}) \times \mathrm{GDPdefl}(2011\ \mathrm{price}) / \mathrm{GDPdefl}(\mathrm{yearX\ price})$$

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 organization 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 the 100%, due to some legitimate deductions of the level of 15%. Damage level less than 20% is not paid and, thus, is not included in the insurance damage payments. The organization covers all crop species systematically cultivated in the country. A critical parameter concerning the consistency of data provided by the Greek insurance organization is that "insurance rule of the rural production" remained unchanged from the beginning of GAIO's operation 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-hours. From these gridded data, points representative for 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-hour time intervals was used in the present analysis.

2.2 Spatial and temporal distribution of frost related damages

Monetary compensations have been aggregated at prefecture level in order to examine the spatial and temporal distribution of the cost 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 cost by meteorological phenomenon shows that overall, during the period 1999-2011, frost is the most damaging one, accounting for 34% of the total insured crop losses (Figure 1), followed by hail (26%) and heavy rainfall (22%). The total cost of frost events is 970 million euros. As illustrated in Figure 2, insured crop losses due to frost vary widely between years, with damages being as low as 2 million euros in 1999 and as high as 290 million euros in 2003. The annual variability, however, cannot be statistically assessed, 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 the pressure level of 850 hPa on the financial cost of crop production damages, for two different regions of the country, allocated 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 mentioned also in section 2.1, that losses covered by GAIO represent approximately the 85% of total direct crop losses.

The spatial distribution of damage costs caused by frost events is depicted in Figure 3, showing the overall damage cost that occurred to each prefecture. For presentation purposes the costs have been grouped in four ranges. As can be seen, the selected regions in north and south 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 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).

Monthly distribution of frost events is presented in Figure 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.

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 there have not occurred any significant changes during the last decade. Specifically, in the north 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.

3.1 Measures

Table 1 presents descriptive statistics for damage cost (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 daily level between 1999 and 2009, and derives as the aggregation of the respective total daily damage records at prefecture level. Frost events with damage cost below 1,000 euros have been excluded from subsequent analysis. These events, which represent the 17% of total frost events that occurred in the two regions, are considered to be extremely localized 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 cost caused by frost events in each region, tmin data have been allocated in three groups of different temperature ranges, with the aim to identify 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 on explaining the crop damage severity. The three minimum temperature levels, tmin_1, tmin_2 and tmin_3, correspond to the highest, medium and low 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 stage of crops in each region. Season 1, 2 and 3 correspond to winter, spring and autumn months (excluding September). Months between June and September were excluded as the number of frost damaging events attributed to these months is of minor importance (1.3% in total, considering both regions).

Consistent to the previous methodological approach, the estimation of the damage probability and its magnitude relatively to the temperature levels required the grouping of the real damage costs in three categories that represent different damage severity (DS) levels. Specifically, DS1, DS2 and DS3 levels refer to the lower 50%, the middle 40% and the upper 10% of the cost data-series respectively (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 independent variable (cost) to its natural logarithm to normalize 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 variation between the second and third categories for both 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 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 north 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 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 south region. Concerning the season variable, the analyses show that overall, seasonality affects damage cost. Specifically, for both regions, two of the three pairs of groups produce different effects on cost at a statistically significant level.

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

To produce the probability of a frost event to occur, we used a dichotomous variable DSi as the dependent variable. DSi takes values of 0 (no cost damage was recorded at 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 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 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 north region and to the upper 50%, the medium 42% and the lower 8% of tmin data in the case of the south 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 further investigate variations between the different seasons, we run separate logit regression for each season and region (additional statistical information is given in Appendix, TableA1).

To obtain the predicted probabilities of a cost to occur 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 to occur (i.e., presence of damage cost), the next set of analyses aims to predict the probability of a certain level of cost damage to occur (i.e., magnitude of cost damage) at each temperature level. Note that days with no damage cost occurrence were eliminated from the analysis. Thus, the produced probabilities are referring to the days with damage costs.

For the specific analysis, DS was used as the dependent variable. Consistent to the previous analysis, we performed an overall analysis by controlling seasonality while also running separate analysis for each season. DS consists of three groups that indicate low, medium and high levels of cost damage. Due to the ordinal nature of the variable, a generalized 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 Appendix, Table A2).

To obtain the predicted probabilities of a certain level of damage cost to occur at each level of temperature, we used a margin analysis after performing each generalized 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 to occur at each temperature level. Therefore, for the north region, if a certain day the temperature falls into the first category (i.e., high temperature), then the probability of low DS (DS1) to occur is 57%, the probability of medium DS (DS2) to occur is 35% whereas the probability of high DS (DS3) to occur is 8% (the sum of probabilities is 100%).

3.3 Validation of the logistic model

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

The results of the logistic regression analysis, presented in section 3.2, have been used to establish the dichotomy of risk/no risk of frost events to occur. It was considered that probabilities under 50% correspond to events for which no cost is expected, while probabilities over 50% permit for a warning of frost damaging event (López et al., 2007). Based on this criterion and the results shown in Table 5, warning for possible crop damages 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 cost to occur for both regions. Regarding the tmin_3 level, the logistic model predicts 61% and 63% probability of damaging event in the north and south respectively, which permit for a warning when the expected temperature at 850 hPa level is lower than the tmin_3 threshold.

4. Discussion

The first objective of the present study was to answer whether and how the level of the minimum temperature at the pressure level of 850 hPa relates to crop production damages. This is a critical issue before moving forward, because it defines the importance of all 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 north and south region under examination. Therefore, T850 is proved to be a parameter that can be directly linked to the development and magnitude of frost damaging 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 to provide warnings for frost risk with potential crop damages.

A more analytical examination of the regression results (Table 4) shows that the different tmin levels associate with quite different magnitude of damage costs. Especially when moving from the middle or high range 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 (north and south). For the north region, it seems that the critical threshold is only one and particularly the low tmin level, while for the south region, 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 cost when comparing spring time (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 north region, are more sensitive in spring and autumn (Snyder, R. L. 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. In the south, 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 associate with higher cost. According to Rodrigo (2000), freezing injuries to fruit trees can be associated with low temperatures prior to dormancy in the fall, in midwinter during dormancy, or during and after budbreak in the spring. Yet, in temperate climates, losses due to frosts during bloom are usually more important than those due to low winter temperatures. However, in the period 1999-2009, spring and autumn in the south region exhibited approximately the same rate of financial losses and similar rates of daily losses due to crop damages during frost events (41 and 45 million euros for spring and autumn frost events, respectively), which partly explain the regression analysis outcomes.

In what concerns the predicted probabilities of a cost to occur at each level of tmin, the analyses show that as tmin falls from higher to lower levels, the likelihood for crop damages to occur increases significantly, regardless of the season (Table 5). Predicted probabilities for a damage cost to occur taking seasonality into account, differentiate slightly between north and south (Table 5), with the exception of springtime low temperature records for which the probability for 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, namely the probability for any cost to occur is high specifically when tmin falls in 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 Figure 5 the number of days that correspond to tmin_3 level, for the period 1999-2009, and associate or not with crop damages (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) associate with the occurrence of crop damages. This analogy is obviously responsible for the high probability of any cost to occur in the low tmin level. Accordingly, the respective proportions for spring and winter lead to lower or much lower probabilities for crop damages.

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 as warning only for low and medium DS. Spring in the north gives noticeable probabilities also for 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 case of a frost event. The severity of a frost damaging event during autumn is expected to be considerably high in the south only for low tmin records, with a probability over 50%. Significant damages are not expected in case of high tmin. However, crop damages have occurred even when T850 is high. Actually, the 25% of frost events in both regions relate to high tmin values and corresponds to the 13% of total insured crop losses (Figure 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 for the probability of the occurrence of a cost damaging event- has been performed, as already mentioned, only for events belonging in the low tmin_3 level. Overall, in the period 2010-2011, 140 daily frost events with crop damages amounting for 26.8 million euros occurred in the two regions examined, 22 of which relate with the low tmin threshold (tmin_3). Indeed, 65 events with a total cost of 24.4 million euros occurred in the south and 75 events with a cost of 2.4 million euros in the north. As the events in the north were mainly low daily cost during the period 2010-2011, the validation will be restricted in the south and for the events with daily cost exceeding 100,000 euros.

During the validation period 16 events with cost exceeding 100,000 euros occurred in the south region, 6 out of which (accounting for 37%) of the cases were in the tmin_3 category. Although only for the 37% of the events there would have been issued a warning, these events accounted for the 79% of the total cost 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 in the south region, the False Alarm Ratio (FAR), that represents the fraction of the predicted events that did not actually occur, has been calculated for the same validation period and equals 0.47. 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% 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 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 relatively to different temperature ranges. Overall, results are better for the north region. Specifically, regression analysis of the relationship between tmin and cost resulted in higher explanatory power (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 in what concerns the probability for any cost to occur 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 frost damaging 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 in the low tmin_3 level. The analysis of the cost damaging events in the south 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 upon the agriculture risks assessment and management. To a large extent, the potential for frost damage depends on local conditions and, thus, it is difficult to be assessed due to the uncertainty included in weather forecasts. It is in the future plans of the authors to further assess the outcomes of the present analysis, while frost events and agriculture damages will keep on being systematically observed as part of the authors' research on weather-related risks in Greece and subsequent socioeconomic impacts (Papagiannaki et al., 2013).

Acknowledgements

The authors acknowledge the Greek Agricultural Insurance Organization (GAIO) and particularly the Director of Research and Application Mr. Ghizlis J., as well as Mr. Chrysanthakis J. for the provision of crop damage announcements and the respective monetary compensations for the period 1999-2011. The European Centre for Medium-Range Weather Forecasts is acknowledged for making available the ERA-Interim reanalyses fields.

Appendix

To enhance the robustness of our methodology and 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 been also performed for a different grouping of damage severity, where 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 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 generalized ordered logistic models. In all model, except one, the prob>chi2 is significant at the 5% level, indicating a perfect fit of the data.

References

European Commission: Regions 2020 – the Climate Change Challenge for European Regions, European Commission, Directorate General for Regional Policy, Brussels, 2009.

Barthel, F. and Neumayer, E.: A trend analysis of normalized insured damage from natural disasters, Climatic Change, 113, 215–237, 2012.

Berthet, C., Dessens, J., and Sanchez, J. L.: Regional and yearly variations of hail frequency and intensity in France, Atmos. Res., 100, 391–400, doi:10.1016/j.atmosres.2010.10.008, 2011.

Botzen, W. J. W., Bouwer, L. M., and van den Bergh, J. C. J. M.: Climate change and hailstorm damage: Empirical evidence and implications for agriculture and insurance, Resour. Energy Econ., 32, 341–362, doi10.1016/j.reseneeco.2009.10.004, 2010.

Changnon, S.: Increasing major hail losses in the US, Climatic Change, 96, 161–166, 2009.

Changnon, S.: Catastrophic winter storms: an escalating problem, Climatic Change, 84, 131–139, 2007.

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M. A., 5 Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A. C. M., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A. J., Haimberger, L., Healy, S. B., Hersbach, H., Hólm, E. V., Isaksen, L., Kållberg, P., Köhler, M., Matricardi, M., McNally, A. P., Monge-Sanz, B. M., Morcrette, J. J., Park, B. K., Peubey, C., de Rosnay, P., Tavolato, C., Thépaut, J. N., and Vitart, F.: The ERA-Interim reanalysis: configuration and performance of the data assimilation system, Q. J. Roy. Meteor. Soc., 137, 553–597, doi:10.1002/qj.828, 2011.

EC: Agricultural Insurance Schemes, European Commission, Joint Research Centre, modified 2008, 2006.

Eccel, E., Rea, R., Caffarra, A. and Crisci, A.: Risk of spring frost to apple production under future climate scenarios: the role of phenological acclimation, International Journal of Biometeorology, 53, 273-286, doi:10.1007/s00484-009-0213-8, 2009.

Giannakopoulos, C., Kostopoulou, E., Varotsos, K., Tziotziou, K., and Plitharas, A.: An integrated assessment of climate change impacts for Greece in the near future, Reg. Environ. Change, 11, 829–843, doi:10.1007/s10113-011-0219-8, 2011.

Gobin, A.: Impact of heat and drought stress on arable crop production in Belgium, Nat. Hazards Earth Syst. Sci., 12, 1911–1922, doi:10.5194/nhess-12-1911-2012, 2012.

Gobin, A., Tarquis, A. M., and Dalezios, N. R.: Preface "Weather-related hazards and risks in agriculture", Nat. Hazards Earth Syst. Sci., 13, 2599–2603, doi:10.5194/nhess-13-2599-2013, 2013.

Hair, J. F., Tatham, R., and Anderson, R. E.: Multivariate Data Analysis, Academic Internet Publ., 2006.

IPCC, 2012: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation, A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change, edited by: Field, C. B., Barros, V., Stocker, T. F., Qin, D., Dokken, D. J., Ebi, K. L., Mastrandrea, M. D., Mach, K. J., Plattner, G.-K., Allen, S. K., Tignor, M., and Midgley, P. M., Cambridge University Press, Cambridge, UK, and New York, NY, USA, 582 pp., 2012.

López, L., García-Ortega, E. and Sánchez, J. L.: A short-term forecast model for hail, Atmos. Res., 83, 176-184, doi:http://dx.doi.org/10.1016/j.atmosres.2005.10.014, 2007.

Moonen, A. C., Ercoli, L., Mariotti, M., and Masoni, A.: Climate change in Italy indicated by agrometeorological indices over 122 years, Agr. Forest Meteorol., 111, 13–27, doi:10.1016/S0168-1923(02)00012-6, 2002.

Nannos, N., Bersimis, S., and Georgakellos, D.: Evaluating climate change in Greece through the insurance compensations of the rural production damages, Global Planet. Change, 102, 51–66, doi:10.1016/j.gloplacha.2013.01.006, 2013.

Papagiannaki, K., Lagouvardos, K., and Kotroni, V.: A database of high-impact weather events in 5 Greece: a descriptive impact analysis for the period 2001–2011, Nat. Hazards Earth Syst. Sci., 13, 727–736, doi:10.5194/nhess-13-727-2013, 2013.

Rigby, J. R. and Porporato, A.: Spring frost risk in a changing climate, Geophys. Res. Lett., L12703, doi:10.1029/2008gl033955, 2008.

Rodrigo, J.: Spring frosts in deciduous fruit trees – morphological damage and flower hardiness, Sci. Hortic., 85, 155–173, 2000.

Rosenzweig, C., Tubiello, F. N., Goldberg, R., Mills, E., and Bloomfield, J.: Increased crop damage in the US from excess precipitation under climate change, Global Environ. Change, 12, 197–202, doi:10.1016/S0959-3780(02)00008-0, 2002.

Ruiz-Ramos, M., Sánchez, E., Gallardo, C. and Mínguez, M. I.: Impacts of projected maximum temperature extremes for C21 by an ensemble of regional climate models on cereal cropping systems in the Iberian Peninsula, Nat. Hazards Earth Syst. Sci., 11, 3275-3291, doi:10.5194/nhess-11-3275-2011, 2011.

Saa Requejo, A., García Moreno, R., Díaz Alvarez, M. C., Burgaz, F., and Tarquis, M.: Analysis of hail damages and temperature series for peninsular Spain, Nat. Hazards Earth Syst. Sci.,11, 3415–3422, doi:10.5194/nhess-11-3415-2011, 2011.

Scheifinger, H., Menzel, A., Koch, E., and Peter, C.: Trends of spring time frost events and phonological dates in Central Europe, Theor. Appl. Climatol., 74, 41–51, doi:10.1007/s00704-002-0704-6, 2003.

Snyder, R. L. and de Melo-Abreu, J. P.: "Frost Protection: fundamentals, practice and economics" Volume 1., Food and Agriculture Organization of the United Nations, FAO, 2005.

Snyder, R. L., de Melo-Abreu, J. P., and Matulich, S.: Frost Protection: fundamentals, practice and economics, Volume 2. Food and Agriculture Organization of the United Nations, FAO, 2005.

Tolika, K., Anagnostopoulou, C., Maheras, P., and Vafiadis, M.: Simulation of future changes in extreme rainfall and temperature conditions over the Greek area: A comparison of two statistical downscaling approaches, Global Planet. Change, 63, 132–151, doi:10.1016/j.gloplacha.2008.03.005, 2008.

UNISDR: Terminology on disaster risk reduction, United Nations, 2009.

Table 1. Descriptive statistics for the period 1999-2009

Variable	Region	N	min	max	mean	st.dev.
Tmin (°C)	North	523	-18.16	14.14	-2.12	5.42
	South	534	-13.15	17.69	0.49	5.70
Cost (€)	North	523	1,019	$1.09\text{x}10^8$	$6.90\text{x}10^5$	$5.89\text{x}10^6$
	South	534	1,017	$6.15\text{x}10^7$	$5.41\text{x}10^5$	$3.17\text{x}10^6$

Table 2. Levels of minimum temperature for the two regions (^oC)

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 1000 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

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 unstandardized regression coefficients, with standard errors in parentheses

[b] the beta coefficients for these variables derive when repeating the analysis to include the omitted categories

+$p<.10$, * $p < .05$, ** $p < .01$, *** $p < .001$

Table 5. Probabilities of cost to occur for each level of temperature

	Probability of cost damage to occur[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 to occur = 1-Probability of cost to occur

[b] Autumn, winter and spring

* p < .05, ** p < .01, *** p < .001

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

North[a]		DS1	DS2	DS3
	All seasons[b]			
	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 < .05, ** p < .01, *** p < .001

Table A1. Fit statistics for logit regressions

Models	N	LR chi-2	Prob>chi2	Pseudo R2
North				
All seasons[a]	2,676	439.96	<0.00	0.17
Winter	993	106.85	<0.00	0.09
Spring	1,012	104.64	<0.00	0.14
Autumn	671	64.11	<0.00	0.15
South				
All seasons[a]	2,676	312.92	<0.00	0.12
Winter	993	160.39	<0.00	0.13
Spring	1,012	37.48	<0.00	0.04
Autumn	671	37.54	<0.00	0.08

[a] Autumn, winter and spring

Table A2. Fit statistics for generalized ordered logit regressions

Models	N	LR chi-2	Prob>chi2	Pseudo R2
North				
All seasons[a]	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[a]	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

[a] Autumn, winter and spring

Fig.1. Distribution of insured crop losses by meteorological phenomenon (1999-2011)

Fig.2. Annual distribution of insured crop losses due to frost events, for the period 1999-2011 (in million euros)

Fig.3. Insured crop losses due to frost events by prefecture (1999-2011)

Fig.4. Monthly distribution of insured crop losses due to frost events, for the period 1999-2011 (in million euros)

Fig.5. Number of days with low tmin observations (tmin_3 level) by region, associated or not with crop damages (1999-2009)

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

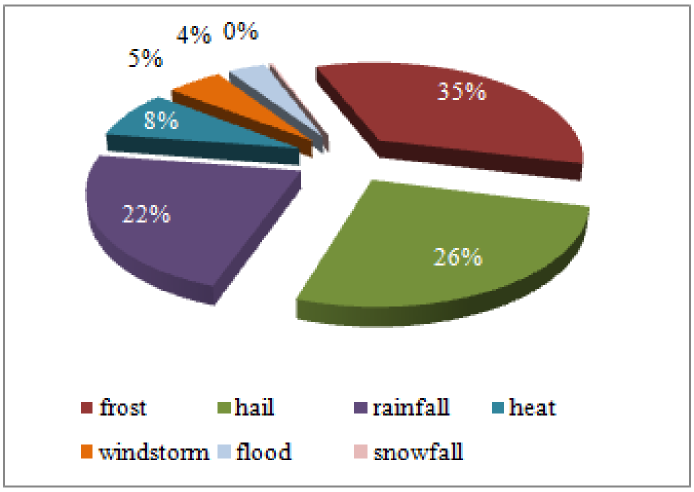

Fig.1. Distribution of insured crop losses by meteorological phenomenon (1999-2011)

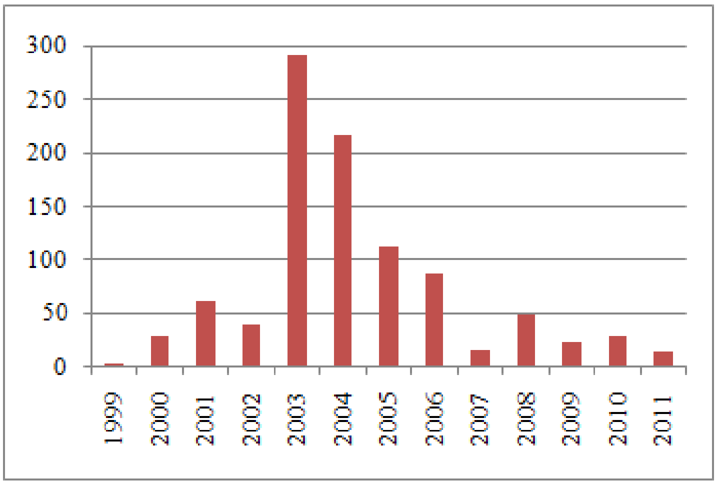

Fig.2. Annual distribution of insured crop losses due to frost events, for the period 1999-2011 (in million euros)

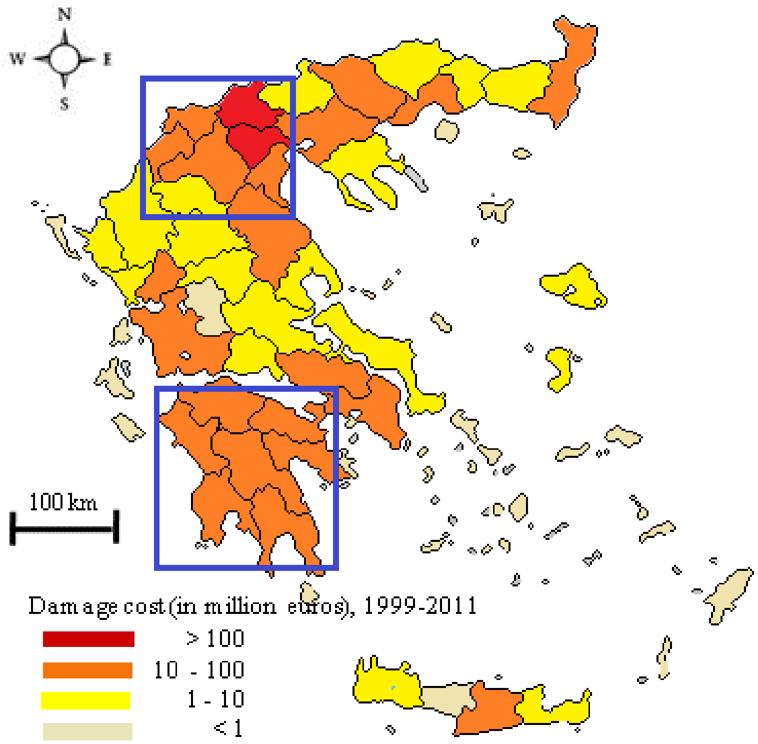

Fig.3. Insured crop losses due to frost events by prefecture (1999-2011)

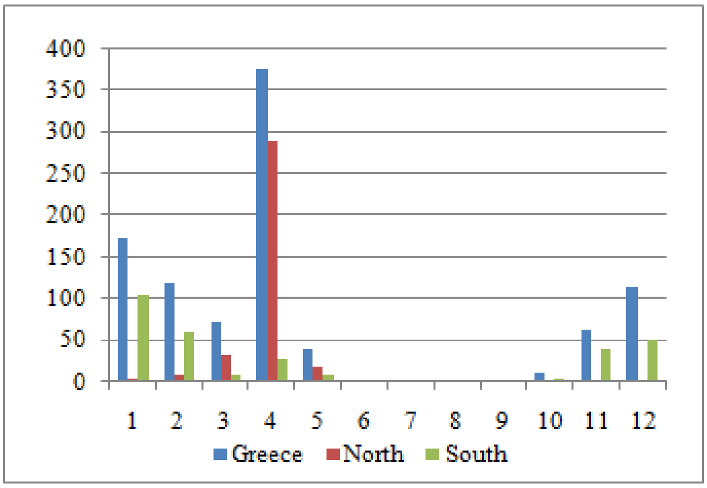

Fig.4. Monthly distribution of insured crop losses due to frost events, for the period 1999-2011 (in million euros)

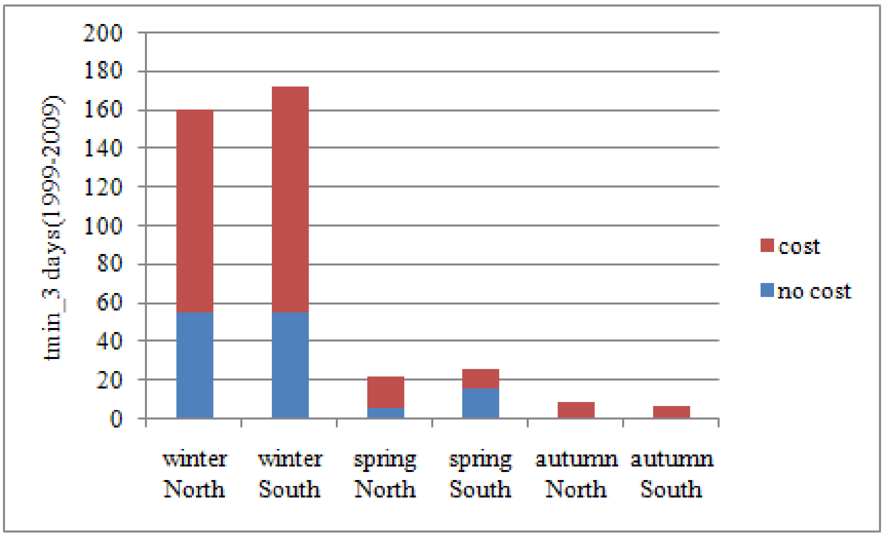

Fig.5. Number of days with low tmin observations (tmin_3 level) by region, associated or not with crop damages (1999-2009)

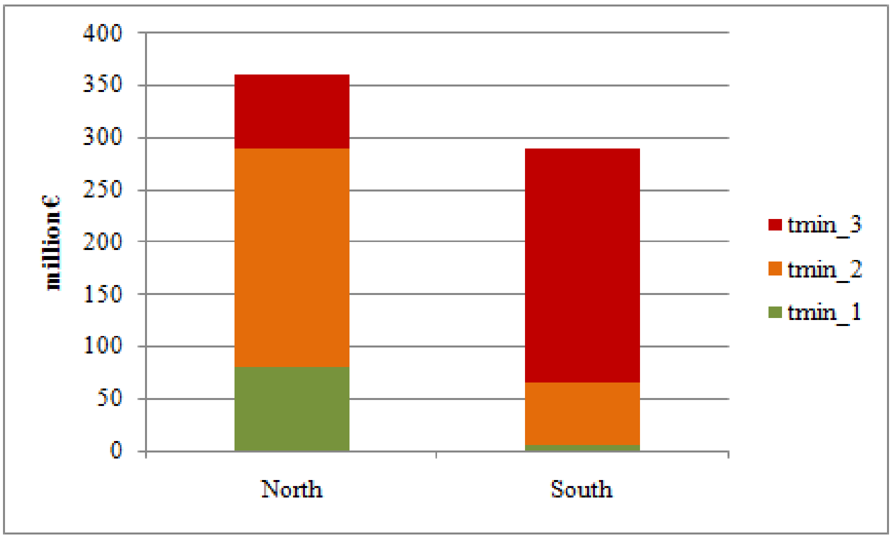

Fig.6. Distribution of frost-related insured crop losses by tmin level (1999-2009)