Modelling the effects of meteorological and geographical drivers on damage from late radiation frost on apple trees in Northeast Iran

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Abstract: *Late frosts occurring in spring create significant bud damage and decrease yield of fruit trees, especially apples, in Northeast Iran. Assessment and risk modelling of late radiation frost damage would be useful to manage and decrease the damage. In order to model frost damage risk, 12 driving variables were selected, including meteorological (minimum temperature, temperature decrease rate, temperature increase rate, date of frost, cumulative degree days, area below zero line, and frost duration) and geographical ones (elevation, longitude, latitude, aspect, and slope). Three damaging radiative frosts were detected in the period of apple flowering time, 20 April 2003, 8 April 2005, and 28 March 2005 cases. Required meteorological data were collected from nine meteorological standard stations located in the apple cultivation area of Northeast Iran. Linear multiple regression was used to model the relationships. Each parameter was spatially interpolated and estimated according to a 5 by 5 km grid in order to extract input data for the model. The regression equation is significant at the level of 5%. This equation fulfils the aim to assess and map frost risk damages for apple production. The regression equation of observed and predicted frost damage risk obtained a correlation index of 0.92.*
Keywords: *late spring frost, minimum temperature, linear multiple regression, Iran, apple.*

Riassunto: *Nell'Iran nordorientale le gelate tardive creano significativi danni alle gemme e diminuiscono il raccolto degli alberi da frutto, specialmente sul melo. Una stima e una modellistica del rischio del danno da gelate radiative tardive può risultare utile per gestire e diminuire tale danno. Per modellizzare il rischio di danno, sono state selezionate 12 grandezze, che comprendono variabili meteorologiche (temperatura minima, tasso di diminuzione della temperatura, tasso di aumento della temperatura, data della gelata, gradi giorno cumulati, area sotto la linea dello zero, durata della gelata) e geografiche (altitudine, latitudine, longitudine, esposizione e pendenza). Sono state selezionate tre gelate radiative che hanno provocato danni nel periodo della fioritura: 20 aprile 2003, 8 aprile 2005 e 28 marzo 2005. I dati meteorologici necessari sono stati ricavati da 9 stazioni meteo convenzionali nel nordest iraniano. È stato quindi creato un modello regressivo multilineare per le relazioni agenti - danno. Le variabili usate per creare il modello sono state spazializzate e stimate secondo una griglia di 5 km x 5 km. L'equazione lineare risultante è significativa al 5%. Questa equazione soddisfa l'obiettivo di mappare quantitativamente i rischi di danno da gelo sulla coltivazione del melo. L'indice di correlazione fra dati osservati e simulati è pari a 0.92.*
Parole chiave: *gelate tardive primaverili, temperature minima, modelli lineari multiregressivi, Iran, melo.*

1. INTRODUCTION

Apple is one of the most important crops of the Khorasan Razavi province, Iran. The entire cultivated area in the province is over 16000 hectares (www.koaj.ir). There is a lot of apple farms in the region, having different dimensions, in general ranging from 1 to 5 ha. The apple variety mainly grown in Northeast of Iran is Golden Delicious.

Apple trees are well adapted to cold climates. Thanks to winter hardening, they can stand temperatures lower than -40 °C (Lindén *et al.*, 1996). In general, such temperatures are never attained where apple is grown; however, if the frost event takes place during the growing season, relatively severe frosts can cause damage, particularly during the reproductive cycle (Porteous, 1996). This adversity also affects apple production in Iran (Farajzadeh *et al.*, 2010), while for other crops in general, frost can be an adversity even in areas of the world which are more typically characterized by general warm climatic conditions, like Brasil (Avissar and Mahrer, 1988a) and Turkey (Erlat and Türkes, 2011). In the spring frost of March 2007 about 11000 hectares of fruit trees suffered damage, including 10000 hectares devoted to apple production in Northeast Iran. The amount of damage, based on declared Agriculture Organization of Khorasan Razavi province

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(www.koaj.ir), was 1.7 Million USD. Frost damage of agricultural products depends on location, time, product type and environmental conditions. What factors determine the damage, and the contribution of each driver to the occurrence of frost, are important issues to be investigated. The damage rates depend on static features such as geographic and topographic characteristics of a region, and on dynamic features such as intensity and duration of frosts. Thus, by quantifying the effective role of single agents in the frost occurrence, the risk of damages to a specific crop in a particular geographic area could be zoned.

Many studies have reported the role of meteorological and geographical parameters on frost damage risk. For example, Bootsma (1976) studied minimum temperatures and risk of frost in the mountainous lands in Canada. He concluded that the average estimated frost dates occurring in the valley bottom were 34 days later in spring and 39 days earlier in fall than at higher elevations. Avissar and Mahrer (1988b) developed a three-dimensional model to simulate the local scale micro-climate zones near ground level during the occurrence of radiative frost nights in non-uniform lands. Effective parameters of this model included topography, vegetation, soil humidity, wind speed and direction, and air humidity. Kajfez (1987) defined a relationship between the first occurrence of early autumn frost date and elevation. Laughlin and Kalma (1988) studied minimum temperature measured over three consecutive winters in an open area. They showed that the minimum air temperature changes with height, mean wind speed at night, the total net radiation at night, and minimum temperature estimated over the hill. Therefore, it was possible to calculate frost risk with weather data, and regional and local land analysis. Zinoni *et al.* (2002) conducted a climatological and orographic study to identify areas prone to frost and determine characteristics of frost events in the period April 1987 to March 2000 for 161 meteorological stations in the Emilia-Romagna region, Italy. They determined correlations among climatic and orographic variables and defined a significant correlation between the mean minimum temperature during the frost and the relative height from valley bottom. Richards and Baumgarten (2003) showed that the spatial distribution of radiation frosts is closely associated with topographic patterns. They prepared a minimum temperature map by using GIS modelling and factors such as ground cover, slope, elevation, latitude, and distance to the sea. Madelin and Beltrando (2005) studied spring late frost risk hazard zonation in grape vineyards in France. They used a digital elevation model to create a minimum temperature distribution map in the study area based on 20 meteorological station data. Eccel *et al*. (2008), aiming at late frost spatial modelling, measured ground temperature by airborne thermal infrared images during a strong thermal inversion episode in a fruit-growing area, showing the existence of a clear geographic pattern in the distribution of minimum temperature. All of these studies highlight the role of micro-climate and geographical parameters on frost risk.

In recent years, frost studies in Iran, despite the importance and amount of damage caused by this adversity to fruit production in the country, have been somewhat limited, mostly considering just statistical occurrence and synoptic aspects. Frost was first studied in Hashemi (1977) for the late (spring) and early (autumn) frosts occurring in Iran, based on data from 17 meteorological stations. Alizadeh *et al*. (1994) studied first and last occurrences of frosts at 15 weather stations of the Khorasan province. These studies were based on single sites, and no attempt was made to obtain regional rules. All previous frost studies in Iran measured the relationship of frost intensity to the frost damage and estimated the various probabilities of occurrence in the form of statistical distributions. No investigation on the assessment of the effects of forcing agents on frost damage was undertaken till now in Iran.

The purpose of this research is the quantitative assessment of this relationship for frost risk damage on apple trees in the Northeast of Iran. This was accomplished by identifying the factors affecting frost damage and integrating them through multiple regression and GIS, providing a model for the evaluation of frost damage hazard. This could be useful for insurance and development practices, as well as for fruit growers, to protect apple trees from frost damage.

2. DATA AND METHODS

2.1 Study area

The study area is part of Khorasan Razavi province of Iran, which is located on the Mashhad plain between the two mountains of Binalud and Hezar Masjed in northeast Iran. The latitude range of the study area is from 36 to 37 degrees North and the longitude is from 58.30 to 60 degrees East (Fig. 1). The approximate area of the study region is about 13000 km^2. It includes the major cities of Mashad,

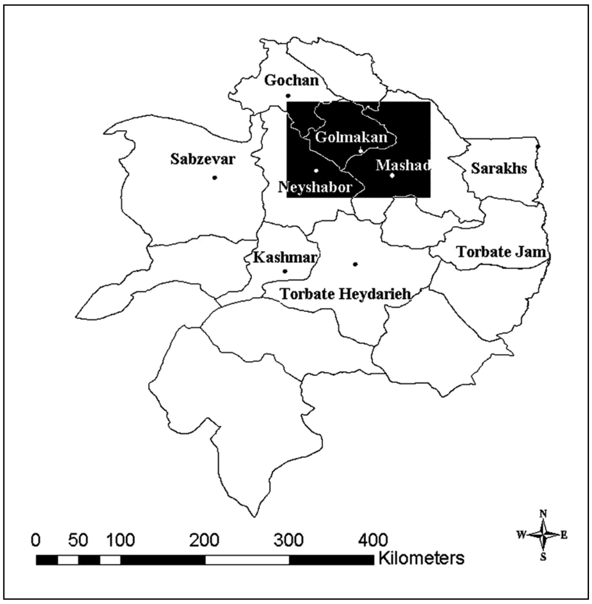

Fig. 1 - Map of Khorasan Razavi province, study area (in black), and meteorological stations (dots).
Fig. 1 - Mappa della provincia di Khorasan Razavi, area allo studio (in nero) e stazioni meteorologiche (punti).

Neyshabor, and Golmakan. This region is one of the most important places for apple production in Iran. The main variety, well adapted for the climate of this region, is Golden Delicious, like in most places in Iran.

2.2 Meteorological and geo-morphological analysis

Data from 9 synoptic stations were used in this study. Golmakan, Mashad and Neyshabor stations are located inside the study area, while the other stations are located outside. The geographical location of stations is shown in Fig. 1. Meteorological data used were minimum temperature, area below the zero line, temperature decreasing rate, temperature increasing rate, day of the year of frost occurrence, cumulative degree days with a 5°C base, and frost duration in hours.
The area below the zero line is the area between the curve of negative air temperature in a day and the zero line, in °C hour.
Temperature decreasing rate is the slope of temperature change from 21:00 to 06:00 local time in the next day (rate of temperature decrease during the nine past hours). Temperature increasing rate is the slope of trend of a temperature line from 6:00 to 15:00 local time (rate of temperature increase during 9 hours after frost). Both factors are in °C h^{-1}.
Other parameters used in modelling included altitude, latitude, longitude, slope, aspect, and frost date, expressed as day of the year (1-365) (Rahimi *et al.*, 2007).

2.3. Phenological modelling

Based on phenological observations from 1999 to 2007 at the agricultural meteorology research station of Golmkan in northeast Iran, an average initial flowering date has been observed for apple in the period 5th to 30th April. The flowering stage is critical for frost damage, because bud resistance to cold suddenly lowers in the proximity of flowering (Farajzade, 2010).
Apple trees need to satisfy chilling requirements in order to end dormancy and to start spring growth and budding. The results of Farajzadeh *et al.* (2010) were used to provide cumulative degree days. According to the mentioned study, 5 °C and 150 degree days were taken as minimum temperature threshold (Tc) and Cumulative Degree Day (CDD), respectively, for the Golden delicious variety of apple (Farajzadeh *et al.*, 2010).

2.4. Analysis of frost damages

About 12 frost events occurred in Khorasan Razavi province in 2003 and 2005 while no late frost occurred in 2004 as shown in Tab. 1. Minimum temperatures recorded at the three stations inside the study area are also shown.
Frosts can be classified into two main types: radiative and advective. In the former case, air cooling is mainly due to the heat loss toward the sky (generally clear). In this conditions air is still, and thermal inversion strongly enhanced, having as a consequence the accumulation of cold air in geographical and morphological basins, and giving rise to a moderate flow in the slope areas. In some cases, this can be lived as a "local advection" episode, although the temperature profile is stable. In the latter case, freezing is strengthened by the irruption of very cold air, advected by moderate to strong winds, originating from the movement of cold continental, polar air. In order to define and distinguish radiative from advective frosts, several factors including wind speed, temperature inversion and cloudiness were used (Davis, 1976). Determination of the temperature inversion requires air temperature data at different heights from the surface of the earth. These data can be obtained from radiosondes, whose records include vertical profiles of 5 weather elements (temperature, air pressure, humidity, wind speed and direction) and are received by the ground station every 5 minutes. These data were available from Mashhad upper

Damage occurrence	Date	Inversion	Minimum Temperature (Mashhad)	Minimum Temperature (Golmakan)	Minimum Temperature (Neyshabor)	Frost Type
frost causing no damage	19 Apr 2003	Normal	-0.6	-1	0	Advective
frost causing damage	**20 Apr 2003**	**Inversion**	**-1**	**-1.6**	**0**	**Radiative**
frost causing no damage	21 Apr 2003	Normal	-1	-0.8	0.6	Advective
frost causing no damage	26 Mar 2005	Normal	1	-1.6	0.6	Advective
frost causing no damage	27 Mar 2005	Normal	-1.4	-3	-0.8	Advective
frost causing damage	**28 Mar 2005**	**Inversion**	**-5.4**	**-4.4**	**-7.2**	**Radiative**
frost causing no damage	29 Mar 2005	Inversion	0	-0.6	-1.8	Radiative
frost causing no damage	30 Mar 2005	Normal	3.2	0	-0.2	Advective
frost causing no damage	7 Apr 2005	Inversion	0.8	-1	-1.6	Radiative
frost causing damage	**8 Apr 2005**	**Inversion**	**-0.6**	**-3**	**-3.2**	**Radiative**
frost causing no damage	9 Apr 2005	Normal	-1	-2.6	-2.2	Advective
frost causing no damage	10 Apr 2005	Normal	1	-1.6	-3.4	Advective
frost causing no damage	11 Apr 2005	Normal	1.6	-0.8	-1.8	Advective

Tab. 1 - Frost events during years 2003 to 2005.
Tab. 1 - Eventi di gelo negli anni dal 2003 al 2005.

air meteorological station, located inside the study area. To determine the presence or absence of temperature inversion, radiosonde reports received at midnight (00:00 local time) were used. The analysis of the vertical profile of temperature allowed the detection of thermal inversion at night. Nights with cloud cover less than 50% and wind speed less than 1.5 ms^{-1} were classified as radiative frost events. Based on these criteria, five frost events, 20th April 2003, 28th and 29th March, and 7th and 8th April 2005, were selected as radiative events, the remaining eight cases being classified as advective events.

Among the five selected frost events, damage

occurred in only three of them, while no damage was reported for the others. Therefore three frost events, 20th April 2003, 28th March and 8th April 2005 were selected as the final radiative frost cases for the study.
For determining spring frost damage on apples for any frost case, the percentage of actual apple yield was divided by the expected apple yield and multiplied by one hundred. These data are surveyed by the Agricultural Insurance Company each year and for every frost event. Company officers' evaluations of frost damage are usually very accurate, being the base for refunding farmers. Protection from pests and deseases are carried out routinely in this region and most of the times there are not any other significant agents that endanger apple production in this area. Hence, if there is no frost damage, yield is little changeable from one year to another. The resolution of primary frost damage is not the same for the whole area, since farm surfaces differ one another, ranging from 1 to 5 ha. This is the information used to produce the damage map for each grid point in the area. For instance, Fig. 2 (created by observations), shows the frost damage for the 20th April 2003 event. The minimum frost damage occurred in the southeast of the study area and the maximum in southwestern parts.

2.5. Building of parameter maps

Among 12 parameters, maps of longitude, latitude, elevation above mean sea level, slope, and aspect were extracted from the Digital Elevation Model (DEM) of the Shuttle Radar Topography Mission Digital Elevation Model - DEM (NASA, 2007) with a resolution of 90 m. Maps were created for each of the other seven parameters. For the frost occurrences, the day of frost occurrence was used as a variable in the regressions. Inverse Distance Weighting (IDW) were implemented in the GIS environment for interpolation (Farajzadeh, 2008).

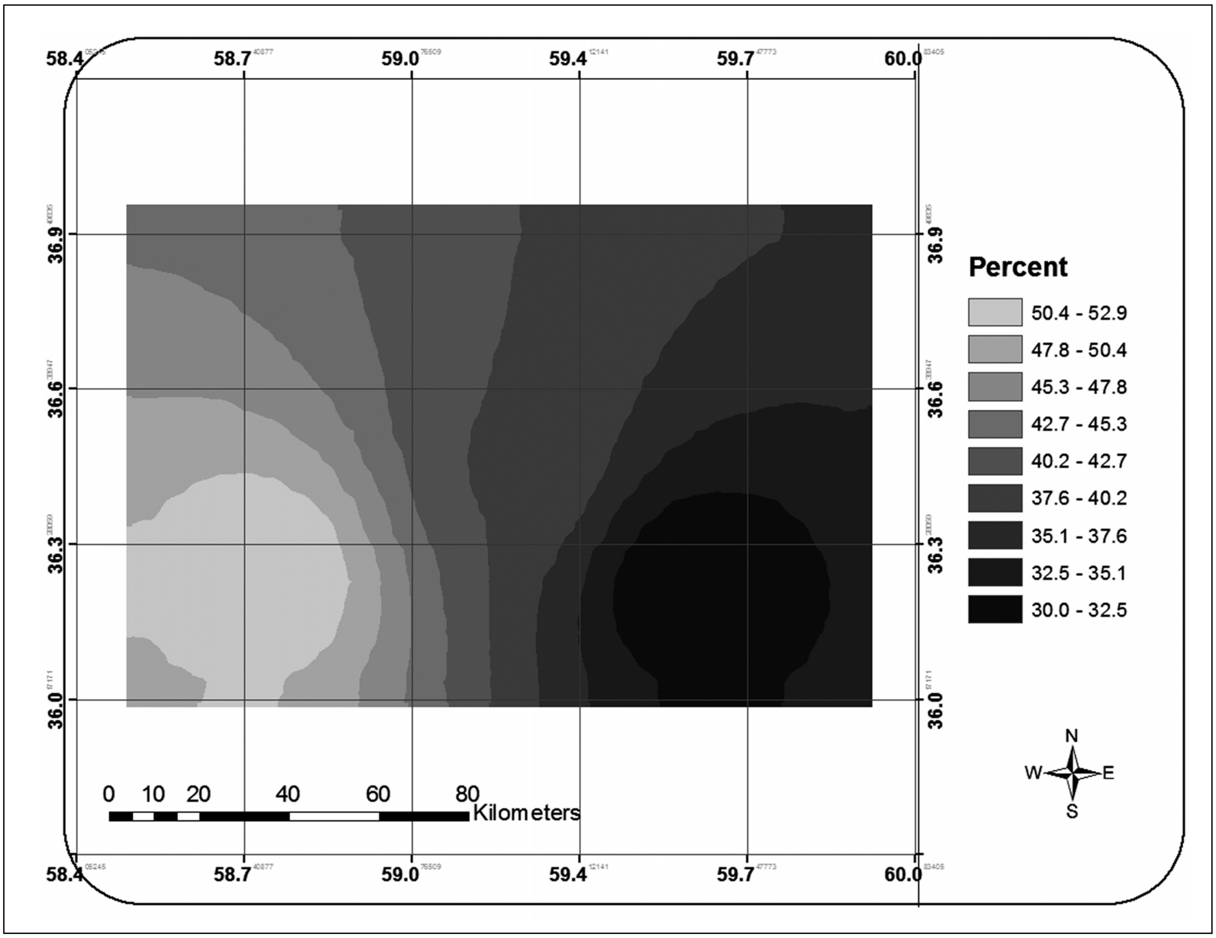

Fig. 2 - Observed frost damage for April 20th, 2003.
Fig. 2 - Danno osservato il 20 aprile 2003.

All parameters for the study area were mapped for each frost event. Spatial interpolation was done to provide enough data to input for regression. The model used these maps as inputs, and the percentage of damaged crop as output. A network of grid points with spatial resolution of 3 minutes (distance 5 km x 5 km) was overlaid on each map. The longitude and latitude axes were divided into 28 and 18 intervals, respectively, since the extent for the study region was 1.5° (longitude) by 1° (latitude). The total number of grid points was 551 (29 by 19). The values of each input and output parameter at every grid point were extracted. Finally, considering the three events, the total number of data points for regression analysis was 551 × 3 = 1653 points.

Parameter	Coefficient	Pearson Correlation
Constant	695.2	---
Longitude	-6.9	-0.23
Altitude	0.009	0.008
Minimum Temperature	-2.63	-0.383
Temperature increase rate	9.3	0.161
Temperature decrease rate	-6.9	-0.066
Area below zero line	0.39	-0.791
Cumulative Degree Days	-0.063	-0.448
Frost Date	-1.75	-1.216

Tab. 2 - Stepwise method regression coefficients and correlations.
Tab. 2 - Coefficienti di regressione e correlazioni per il metodo di regressione "stepwise".

75% of these data were picked up at random, setting up the calibration subset. The rest of data (25%) were processed for the model validation.

2.6. Modelling frosts with linear regression

For modelling and calibration of frost risk occurrences, the influence of all the 12 agents has to be quantified. Multiple regression was used to determine the impact of each of these factors, calculating Pearson correlation coefficients. Four methods of regression (Enter, Stepwise, Forward and Backward) were used to determine the coefficients of the regression equation. Root Mean Square Error (RMSE) statistics were employed for comparison of these methods (Farajzadeh, 2008).
Thus the risk of damage was estimated by using the regression analysis for three frost events based on the equation applied to each grid point. After frost damage risk was assessed for each frost event and estimated at any grid point, frost damage maps were prepared using IDW. In order to study correlations between the two maps, regression equations and correlation coefficients of each equation were obtained for each frost event.
Finally, the flow chart of methodology is sketched in Fig. 3.

3. RESULTS AND DISCUSSION

Some drivers do not to improve significantly the regression model. In order to exclude these parameters a "Stepwise regression" method was applied. The calibration results are shown in table 2, where the correlations of single variables with damage risk are reported.
The multilinear regression equation resulting from the previous analysis is the following:

$$FDR = 695.2 - 2.63Tn + 9.3\ IN - 1.75DOY + \\ + 0.39AR - 6.9DE - 0.063\ DD - 6.9X + 0.009\ Z$$

where Tn is minimum temperature, IN is temperature increase rate, DOY is the date of frost (expressed as day of the year), AR is area below zero line, DE is temperature decrease rate, DD is cumulative degree days, X is longitude and Z is elevation. RMSE of the equation was 1.72 and R^2 was 0.95. The degree of freedom was 5. The role of single drivers is commented in succession.

Minimum temperature (Tn).
Pearson Correlation coefficient between the risk of frost damage and the minimum temperature is — 0.383 (significant with $p < 0.05$): as expected, the lower the temperature, the highest the damage.

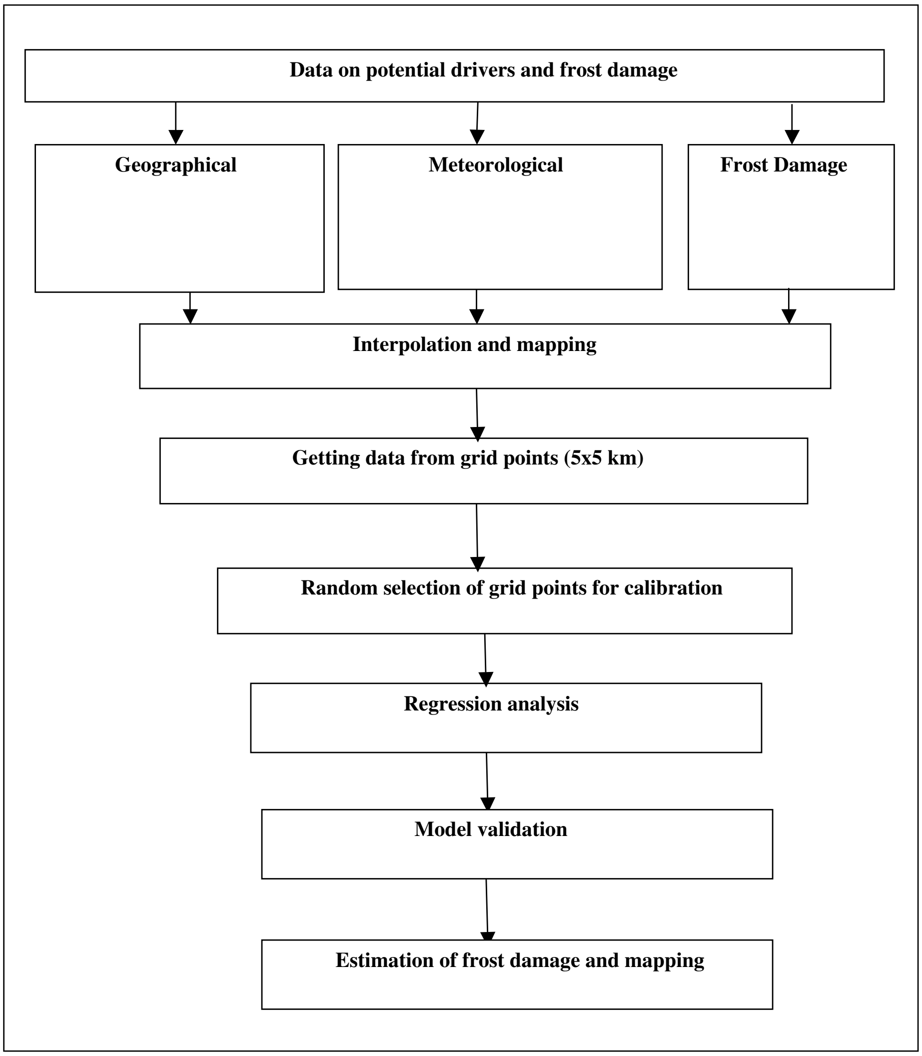

Fig. 3 - Methodology of model creation and validation.
Fig. 3 - Metodologia di creazione e validazione del modello.

Rate of temperature increase (IN)
This variable also has a positive impact on the risk of frost damage. This means that the rate of increasing temperatures after the frost event affects the amount of damage. Snyder (2005) and Ribeiro *et al.* (2006) have reached the same result. The reason for this is that slow melting of ice causes a low rate of the water loss from cells that have suffered extracellular freezing, and can therefore reduce the damage compared to a rapid melting process. If an increase in temperature after the occurrence of a frost event occurs gradually and slowly, it is better and easier for the plant to recover damaged tissues.

Day of the year (DOY)
It has a correlation coefficient equal to -1.216 with the risk of frost damage. Obviously, this negative value shows that the more advanced is the season, the lower is the risk of frost damage. The study period in this investigation was 5th to 30th April, according to the apple flowering date range. As mentioned earlier, the most critical stage of plant growth is flowering time, when the buds increase their vulnerability to frost damage. In the following stages plants do not increase sharply their susceptibility to frost, while temperature has lower and lower probability of attaining freezing values, therefore the risk of frost damage on the crop decreases.

Area below the zero line (AR)
This is the surface enclosed between the daily temperature curve and the line of daily temperature of 0 °C. This quantity has a correlation coefficient of -0.791 with frost damage, showing the direct impact of frost damage with the spread of the freezing area (the wider the below-zero area, the higher the frost damage risk). Of course, the area assumes a high

extent when both the minimum temperature is low and duration of freezing is long, each of the two components increasing the surface of below-zero terrain.

Frost duration (DU)
The correlation coefficient with the risk of damage is 0.664, which indicates the direct impact of frost duration on the amount of damage. These results confirm the findings by Snyder (2005).

Temperature decrease rate before freezing (DE)
It has a correlation coefficient equal to -0.066 with the risk of frost damage. Accordingly, the lower the rate of temperature decrease before the frost event, the greater the damage. No published work regarding the impact of temperature decrease rate before freezing has been found. What appears in this regard as a reasonable justification is the relationship between the rate of temperature decrease with the area under zero line that makes the relationship statistically significant. The lower the rate of temperature decrease to reach a certain minimum temperature, the larger will be the area under the zero line, and definitely, the bud exposure to cold.

Cumulative degree days (DD)
It has a correlation coefficient equal to -0.448 ($p < 0.05$). According to the sign of the correlation coefficient, the less heat units have been accumulated, the greater will be frost damage risk. This is an apparently counter-intuitive result, because frost tolerance decreases as the bud development proceeds. However, the probable explanation is that DD is strongly linked to the date of frost occurrence (DOY), and, in the set of frosts that were considered in this study, the ones with the lowest temperatures are also the earliest. The two independent variables, indeed, enter the regression equation with the same sign.

Longitude (X)
The correlation coefficient is equal to -0.23 for longitude ($p < 0.05$), highlighting higher risk rates at the westernmost areas of the region.

Altitude (Z)
The correlation coefficient between altitude and risk of frost damage equals 0.008 at about the 5 percent level of significance. With altitude increasing, the risk of frost damage also increases. Usually in highlands spring frosts persist later, and early autumn frosts start earlier, than in lower areas. So the frost season is longer in highlands and the frost-free period is shorter. Therefore the period with frost hazard is longer and the frost damage risk will be higher. Snyder (2005), and Loughlin and Kalma (1990) also found this relationship. However, in U- and V-shaped valleys the situation is different because the lowest part of these types of areas is often a cold-air gathering place and a cold spots forms. This leads to radiation frost conditions with cold, stable air.

Latitude (Y), slope (SL), aspect (AS)
No significant correlation was observed between the latitude, slope, and aspect of place with frost damage risk. The effects of slope and aspect on frost damages are significant at a local scale. As we worked at the mesoscale in this study, diversity and changes in slope and aspect was high and hampered significant relationships. Hijmans (1998) in a study to determine suitable areas for planting potatoes in Peru, concluded that there was no significant effect on frost damage by slope. In microscale studies of frost damage, as for a small area, the diversity of slope and aspect are not so high and these two parameters would have a statistically significant correlation.
In order to validate the model, the multilinear regression equation was applied to the 25% of data set aside for this purpose. Fig. 4 shows the correlation of observed and predicted frost damage. R^2 equals 0.84 and is significant at 5% level of probability.

4. CONCLUSIONS

This investigation studied the influences of different parameters on spring frost damage in the Mashhad plain apple cultivated area. Two categories of factors have effects on the risk, and come from meteorological and geographical characteristics of the sites. To determine the effects of potential drivers on the risk of frost damage, linear multiple regression models were built and analyzed. From 12 parameters considered, 7 are meteorological and 5 are geographical. As expected, minimum temperature was found to be the most important and most effective parameter for the frost damage risk, being directly linked with the severity of frost. Terrain slope and frost duration have little importance and seem negligible on frost damage. According to F statistics, the meteorological parameters are more important than the geographic ones. It has been postulated that apple trees have the ability to acclimate their phenological behavior (Rea and Eccel., 2006), but it is also a normal

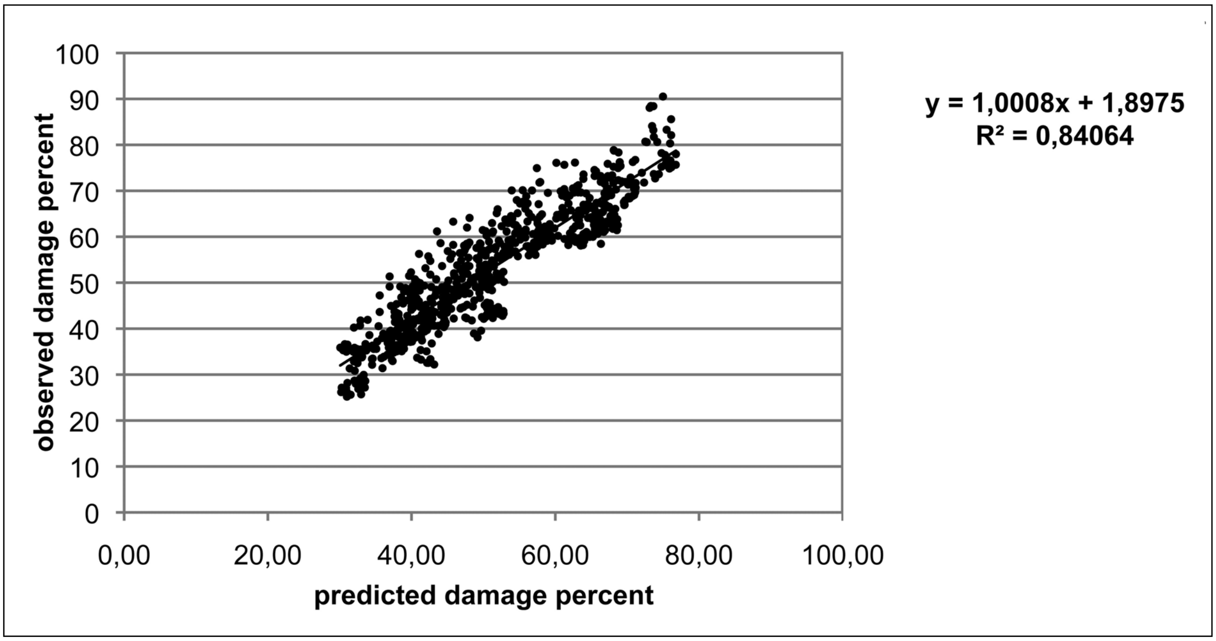

Fig. 4 - Correlation between observed and predicted frost damage (validation data set), according to the multilinear regression equation at Sect. 3 ($R^2 = 0.84$, $p < 0.05$).
Fig. 4 - Correlazione tra danno predetto ed osservato, validazione del modello, secondo l'equazione di regressione multilineare della Sez. 3 ($R^2 = 0.84$, $p < 0.05$).

feature that the lower temperatures at higher altitudes slow down the attainment of the sensitive phenological stage of flowering.

The positive verification of the regressive equation on an independent data set shows that the model is able to quantify the effects of different geographical and meteorological features on apple frost damage risk at the mesoscale in the climatic and geographic context of the region.

This kind of analysis has a general enforceability and can be applied to other natural adversities, such as, drought occurrence, or susceptibility to pest infection (Field *et al*., 2012). Once the drivers of risk are identified, it is possible to model the response of damage to the action of drivers, aiming at the classification of areas in terms of proneness to a specific risk.

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