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Mapping the sensitivity of citrus crops to freeze stress using a geographical information system in Ramsar, Iran

Hasan Zabihi[a,*], Iris Vogeler[b], Zulkarnaini Mat Amin[a], Bahman Ramezani Gourabi[c]

[a] *Department of Geoinformation, Faculty of Geoinformation and Real Estate, Universiti Teknologi Malaysia (UTM), 81310 Johor Bahru, Johor, Malaysia*
[b] *AgResearch, Grasslands Research Centre, Palmerston North, New Zealand*
[c] *Department of Geography, Islamic Azad University of Rasht, Iran*

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ABSTRACT

Citrus, a cold-sensitive plant, often suffers from low temperature, which seriously affects citrus productivity. Environmental constraint factors have mixed impacts on horticulture that differ among the areas, periods and crops. This study presents a statistical analysis to investigate the freeze stress (FS) conditions and morphometry, especially altitude and minimum temperature on citriculture at a regional scale. Based on the temperature isolines map and topography, this paper highlights the impact of altitude and minimum temperature on the citrus crop production using geographic information system (GIS) techniques, statistical analysis and climatic data in Ramsar, Iran over a period of 30 years from 1980 to 2010. This study shows that the suitability varies in relation to the critical temperature and concludes that both minimum temperature and altitude have significant negative impact on citrus crop production. Climate change, in particular, occurring cold fronts in recent years during the citrus harvest time have been complicating this issue and increased the importance of freezes stress (FS). The results highlight that citrus crop orchards were more strongly affected by the minimum temperature, and along with the elevation ranges theses are major challenging factors.

1. Introduction

Climate change can induce an increase in the frequency and intensity of weather events at the global and regional scale (IPCC, 2012). To evaluate the sustainability of economic growth and welfare, it is crucial to have a deeper understanding of how regional economic development affects vulnerability of local communities, that is to say the propensity to be adversely affected by the weather (IPCC, 2012).

Citrus plants are one of the world's most important fruit cash crops. Citrus is commercially grown in more than 100 countries around the world in the tropical, subtropical and borderline subtropical areas, approximately 40°N and 40°S of the equator (CDCGC, 2004; FAO, 2009). Citrus is primarily valued for the fruit, which is either eaten alone (sweet orange, tangerine, grapefruit, mandarin, etc.) as fresh fruit, processed into juice, or added to dishes and beverages (lemon, lime, etc).

Iran has always been a major provider of citrus production in the world. According to FAO, 2007, Iran has the seventh ranking production of grapefruit, lemon and sweet orange, and fifth ranking in mandarin production in the world. Cold temperature causes huge agricultural losses and its effects on crop growth and yield are well known (Beck et al., 2007). Temperature effects are one of the variable environmental factors during at ripening and maturing stages. Exposure to low and very low temperature are one of the most common environmental stresses on plants (Sahin-Cevik and Moore, 2006; Chen et al., 2011; Haghighi et al., 2014; Kalisz et al., 2014; Dürr et al., 2014; Vico et al., 2014; Loel and Hoffmann, 2014) and its productivity is seriously affected by low temperature (Zhang et al., 2005). In citrus low temperature causes chilling and freezing injuries on plants and thus limits crop production and yield (Zhang et al., 2011). The optimal temperature for citrus growth and development ranges from 13 to 37 °C (Wu et al., 2012). The thermal integral was calculated by means of the following formula: IT =(Tm −12.8) dm, where 12.8 represent the base temperature of citrus (Bustan et al., 1996), Tm is the daily average temperature, and dm is the number of days of the month.

The study area has a temperate climate zone, not ideally suited to sub-tropical fruits, such as citrus.

During the last decade, frost damages have become one of the major challenges in the study area (frost event by year of 2008, 2014). Typically, in this region, the harvesting time is coincident with late autumn and early winter seasons (end of November to February). This suggests a likely relationship between the spatial distributions of citrus

* Corresponding author.
E-mail address: hassan.zabihi@gmail.com (H. Zabihi).

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orchards and FS conditions.

On a global scale, minimum temperatures have increased about twice as fast as maximum temperatures (Vose et al., 2005; Skansi et al., 2013). In Spain, Martínez et al. (2010) reported increases in annual minimum and maximum temperatures during spring and summer, and only for maximum temperatures in winter. In France, a mapping of temperature trends has been established by Moisselin et al. (2002). They showed a significant increase in minimum temperatures and moderate increase in maximum ones. Minimum temperatures presented an east-west gradient, whereas maximum temperatures exhibited a north-south gradient.

The present study attempts to determine suitable regions for future planning and how these FS challenges can be addressed by conducting DEM data associated with extreme minimum temperatures as a critical climate variable. Only a few studies have considered the effects of environmental parameters on crop production including climate change (Chartzoulakis and Psarras, 2005; Lobell et al., 2006, 2007a; Tao et al., 2008; Quiroga and Iglesias, 2009; White et al., 2011; Gohari et al., 2013; Smith et al., 2013; Wei et al., 2014; Anwar et al., 2015), low temperature, cold shock, crop load and bud age of sweet orange and mandarin (Valiente and Gene Albrigo, 2004; Barry and van Wyk, 2006; Crifò et al., 2011), air temperature (Lobell, 2007; Thakur et al., 2010; Luo, 2011; Chen et al., 2011; Jumrani and Bhatia, 2014). Current studies have shown that phenological stages are closely related to temperature characteristics of the cropping site during months preceding the phenological evolution (Osborne et al., 2000; Lopez and Dejong, 2007).

This paper, therefore, focuses only on the influence of minimum temperature and altitude as crucial factors in response to citrus crop production. To our knowledge, no research to date has examined the interaction effect of altitude and minimum temperature and applying suitable frameworks on citrus crop at regional scale.

The purpose of this paper are (1) to provide insight of critical minimum temperature and altitude dataset on citrus crop production (2) to determine the impact of minimum temperature and altitude on citrus crop (3) examine the roles of FS and reveal regions prone to FS using GIS techniques. As such the paper contributes to geographical and scientific debates on the mapping of suitable citrus cultivation regions, integrating with climate variable and altitude along with GIS techniqes. Furthermore, this study has policy implication as it identifies regions and districts prone to optimum production and provide policy makers, decision-makers, and growers to feed into a more targeted climate adaptation.

2. Research background and related works

In the area of environmental parameters, Lobell (2007) considered the difference between daily minimum and maximum temperatures (DTR) on rice, maize, and wheat. The aim of his study was to evaluate historical datasets and climate model projections. The relations between average temperatures, DTR and crop yields were assessed. A study by Quiroga and Iglesias (2009) focused on climate risks, including extreme temperatures and precipitation variability, on cereal, citrus, olive and grapevine without focusing on altitude. Statistical models of yield response functions addressed how temperature and precipitation variability affect the crops of a traditional Mediterranean farming system. Responding the critical need for knowledge on crop response to extreme events, Lobell et al. (2007a) analyzed the relationship between temperature and precipitation on 12 major California crop yields, over a period of 23 years. The results showed that recent climatic trends have had mixed effects on crop yields. In USA the effect of changes in temperature, CO2, and precipitation; on crop production was analyzed by Hatfield et al. (2011). They found that the temperature effects on soybean could potentially cause yield reductions in the South US but an increase of 1.7% in the Midwest.

Tao et al. (2008) presented a relationship between climate–yield and the impacts of recent climate trends on crop productivity on a large scale. In their study, major crops (i.e. rice, wheat, maize and soybean) were considered and they found that major crop yields were significantly related to climate during the growing season. A study conducted by Valiente and Albrigo (2004) during the 1999 and 2000 seasons, to monitor the flower bud induction response of two sweet orange trees to naturally occurring winter weather conditions showed that low temperature, was an important factor. They indicated that low temperature inductive conditions resulted in the transition of buds from vegetative to reproductive. Vegetative buds were thus reduced in favour of reproductive buds under low temperature inductive conditions. Similarly, Thakur et al. (2010) reported that cold temperatures are the cause of enormous agricultural losses, especially in sub-tropical and temperate grain crops. The aim of their paper was to describe the effects of low temperature on various stages of the reproductive phase, from meiosis to grain filling, and temperature sensitivity of different reproductive organs. Cold stress during the reproductive phase causes structural and functional abnormalities in reproductive organs, leading to failure of fertilization or premature abortion of seed or fruit (Thakur et al., 2010).

Jumrani and Bhatia, 2014 performed a study on the impact of elevated temperatures on growth and yield of chickpea (*Cicer arietinum* L.). They concluded that for heat tolerance in chickpea, breeding efforts needs to be focused on improving the reproductive efficiency. Chen et al. (2011) investigated whether minimum temperatures increase corn production in China based on correlation and regression analyses of climate records. The results showed that the minimum temperature was the dominant factor to corn production. Mphahlele et al. (2014) found that differences in climatic conditions, altitudes and maturity stages have profound influence on the bioactive compounds of pomegranate fruit.

Thus, in comparison with research efforts found in the literature, our work has the following differences. In this research:

i. We highlight linear regression analysis using GIS techniques for FS monitoring. The purpose is to provide the necessary background to fully understand the requirements of these applications.
ii. The analysis can solve complex problems and adequately consider the relationship between FS, citrus production and spatial distribution of citrus.
iii. Accordingly, this study provides further insight by incorporating a more comprehensive approach to the measurement of both minimum temperature and altitude performance by statistical method that influence on perennial plants including citrus plants.

3. Materials and methods

3.1. Case study

The region investigated in this study is located in the northern part of Iran. It is about 250 km north of the capital of Iran. Ramsar region situated in the west part of Mazandaran province, borders the Caspian Sea to the north and the Alborz Mountains range to the south. The population is approximately 70,000 at the end of 2010 census (statistical center of Iran, 2010). This region is one of the most important citrus production areas in Iran with approximately 7000 ha of citrus orchards. The geographic coordinates of the study area are located between latitudes 36°32′00″ to 36°59′11″ N and longitudes 50°20′30″ to 50°47′12″ E. The total study area covers approximately 729.7 km^2. The altitude of Ramsar County starts at a height of −20 m near The Caspian Sea to 3620 m above sea level. A map of the study area is presented in Fig. 1. This study was conducted from December 2013 to January 2014.

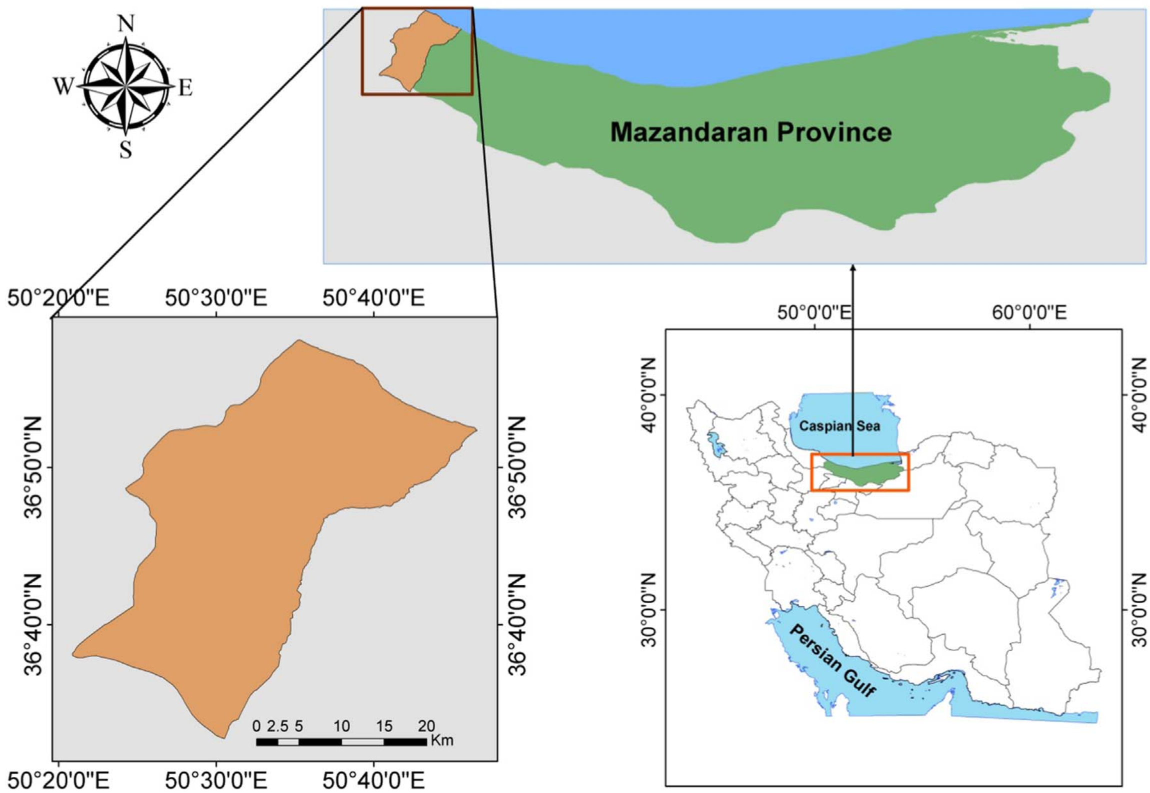

Fig. 1. Location map of the study area.

3.2. Site and geo-climate data

Temperature data and topography have been collected and analyzed from 16 meteorological stations in and around the region. Meanwhile, 30 sample citrus orchards were used in ArcGIS 10 to analyse the spatial distribution of orchards in study area. Temperature isolines data were obtained from the archives of the Ramsar synoptic station statistics, 2007. All meteorological records were subjected to a visual examination for reasonableness, completeness, and any obvious discontinuities.

Furthermore, Feng et al. (2004) objective quality control approaches including tests of spatial and temporal errors and data missing interpolation, were applied. From this analysis we found that the quality of all meteorological records at Ramsar station are sound good for climatological and trend analysis. A digital elevation model (DEM) was produced using ArcInfo (ESRI, 1999), based on data collected in a geological survey of Iran in 2011. Altitude as the terrain attributes was derived from the DEM. In addition, citrus optimum requirements and physiology collected from Ramsar citrus research institute in 2012 were used. Table 1 gives an overview of the spatial database, topographic map including elevation and the minimum temperature as the climate factor. In addition, a 30 years period of minimum temperature was used in Table 2.

Based on the minimum mean temperature Table 2, Citrus would not have any growth from October to April; and indeed, growing activity starts around 13 °C in May and when temperature increase (above 13 °C) the plant starts flowering, loading fruits and leaves. Thereby, based on Table 2, citrus trees typically has growth during the months of May, June, July, August, and September. Although the minimum mean temperature become to 2.2 °C and 1.9 °C in January and February respectively. An outline of two crucial phenological stages of citrus is presented in Table 3.

As a next step, minimum temperature and elevation were imported into Curve Expert software version 1.4 as two negative parameters and analyzed. Curve Expert software employs a linear regression models as well as various interpolation schemes to represent data in the most precise and convenient way. The analysed data were then passed into ArcGIS software (Version 10), which was used to produce a map of FS.

3.2.1. Statistical analysis

Factor analysis was carried out using IBM SPSS Statistics version 20. Pearson's correlation coefficient (r) was used to determine significant relationships between the climatic variable (minimum temperature) and altitudes, and to determine p-value for this model. Similar to regression subsets, it performs an exhaustive analysis of FS variable. According to Table 4 minimum temperature during the four critical months of fruit ripening (November to February) are analyzed the boarderline of moderate regions i.e. 1500 m using spss 20. Temperature changes with regard to a region topography (altitude-temperature equation). The rate of decrease in air temperature with an increase in altitude (typically assumed to be −0.6 °C per 100 m) is

Table 1
Factors used in suitability assessment, data sources and associated factor classes for suitability mapping in Ramsar, Iran.

Sub-classification		Source of data	GIS data type		Scale or Resolution
Spatial database	Data layers		Spatial database	Derived map	Spatial database
Topographic map	Elevation	1:50,000 Topographic map from Iranian cartographic organization, 2013	Line	Elevation	1:50000
Climate data	Min. temp	Ramsar synoptic station statistics, 2013	Line	Isolines map	–

Table 2
The minimum mean temperature (30 years period) of the study area (Ramsar synoptic station statistics, 2013).

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean min temp. (°C)	2.2	1.9	3.4	3.6	13.2	16.0	18.2	19.6	14.1	11.6	7.2	4.9

known as environmental lapse rate (Dobrowski et al., 2009; Fridley, 2009). The results of spss are as following:

Altitude from sea level i.e. 0–1500 m (boundary of moderate value) with 16 data (different elevation) were used in response to minimum temperature (altitude–temperature equation), giving a pearson correlation value of −0.97 (r=−0.97 & p=0), and indicating a strong negative correlation between altitude and temperature. In order to account for observed trends in data, a linear regression as curve estimation in spss was used for extrapolating which is shown in Table 4. Regression are designed to assess consistency between altitude and FS. The selected minimum climatic variables with the strong correlation of altitude confirmed that by decreasing temperature resulting in a significant loss of citrus production and distribution. Thus, more emphasis needs to be given to the relation between FS and altitude. As citrus is sensitive to temperatures of 0 °C (chilling injury and below (FS), the elevation of 700 m is the maximum altitude at which citrus production is secure within the region. To reinforce of this linear regression, the relations between minimum temperature and elevation in the four critical months from 1980 to 2010 are presented in Fig. 2.

The interpretation of Fig. 2 indicates that temperature decrease to 0 °C over 1300 m. consequently, the threshold elevation above 1300 m signify FS conditions in terms of citrus distribution. The regression coefficient value (a and b as obtained in Curve Expert software, Table 5) were used in ArcGIS 10 for the raster calculation in order to create a suitability map with respect to mean minimum temperature and elevation for all months. Accuracy was assessed using root mean square error (RMSE), adjusted R^2, and the Pearson's rank correlation coefficient. We calculated the root mean square error (RMSE) using (Willmott, 1984).

$$\mathrm{RMSE} = \sqrt{\frac{i}{n}\sum_{i=1}^{n}(X(observed) - X(estimated))}^{2} \quad (1)$$

The results clearly indicate that altitude and minimum temperature have significant negative relationships with citrus production. For all the cases, the value of R^2 indicates good fitness of the model. For the normal data set, the correlation coefficient found 0.97 with RMSE of 0.60 that means the strength and direction of the linear relationship between altitudes and temperatures. Correlation coefficient interpretation (r≥0.8) indicate strong relationship between two variables (Cohen, 1988; Hemphill, 2003). In addition, altitude as an independent variable has significant negative relationship with a minimum temperature as a dependent variable. Based on the phenology of citrus fruits (life cycle events) the months of February and January are the time of fruit maturing. Digital elevation model (DEM) of the study is presented in Figs. 3 and 4.

Table 4
Pearson correlation coefficient value obtained for minimum temperature and altitude.

Correlations			
		Altitude	Temperature
Altitude	Pearson Correlation	1	−0.973[a]
	Sig. (1-tailed)		0.000
	N	16	16
Temperature	Pearson Correlation	−0.973**	1
	Sig. (1-tailed)	0.000	
	N	16	16

P-value=0
[a] Correlation is significant at the 0.01 level (1-tailed).

4. Results and discussion

The harvest of citrus which is during in the winter season, at often critical minimum temperature sometimes below zero, which damages the crops (yield and quality), and even can kill the trees. Fig. 5 presents the spatial distribution of citrus orchards in 2010, and the suitability value for citrus crop production in relation to minimum temperature is shown in Fig. 6, based on three different classifications (elevations of 700 m, 1500 m and 2500 m).

The minimum temperature, followed by chilling and FS are critical issues for citrus crop production in the region. Citrus fruits are very sensitive to frost damage, and severe frost kills the citrus trees. Citrus fruits (especially at the ripening stage) can tolerate only 2–3 h the temperature drop from −2 to −3 °C, otherwise the fruits decay. However, frost events have different effects on citrus fruits, different species, growth and citrus trees age (the young trees and adult trees). Based on Figs. 6 and 7, many regions are at risk and apart from zone 1, all regions could be under FS by an unexpected cold front moving from Siberia to the northern part of Iran during late-autumn and winter, dropping the temperature significantly. This needs to be considered in policy for future citrus expansion in the study area. Currently zone 2 is covered by evergreen forest, while zone 3 is covered by bare soil and rangeland. Three agro-ecological zones are classified in relation to minimum temperature in Fig. 7.

Based on Fig. 7. three different altitudes are distinguished, the red color in the lower elevation in the northern regions (less than 700 m) is the only suitable region for citrus crop production in the study area. These regions are solely proposed for citrus planting and future investment. The green color is in the upper elevation (up to 1500 m) with lower temperatures, and is moderately suited for citrus crop production. The blue color over 1500 m with extreme FS is the unsuitable zone (zone 3). In the last years the Ramsar district has seen a significant land use change with and increases in citrus trees

Table 3
The timing of phenological stages and harvesting time for citrus for regions in the temperate Northern Hemisphere (Connellan et al., 2010).

	Autumn			**Winter**		
Phenological stages	Sep	Oct	Nov	Dec	Jan	Feb
Citrus maturing &harvesting		Maturation →				
Citrus maturing &harvesting			Harvest →			

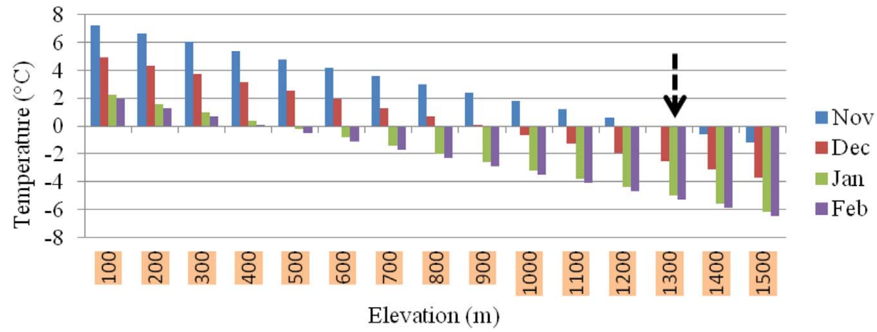

Fig. 2. The relationship between minimum temperature and elevation in the four crucial months using meteorological data 1980–2010.

Table 5
Regression coefficients values between minimum temperature and altitude.

Linear Fit: $y=a+bx$	
Coefficient Data:	
a = 8.34238464711E+000	b = −5.18092468393E-003

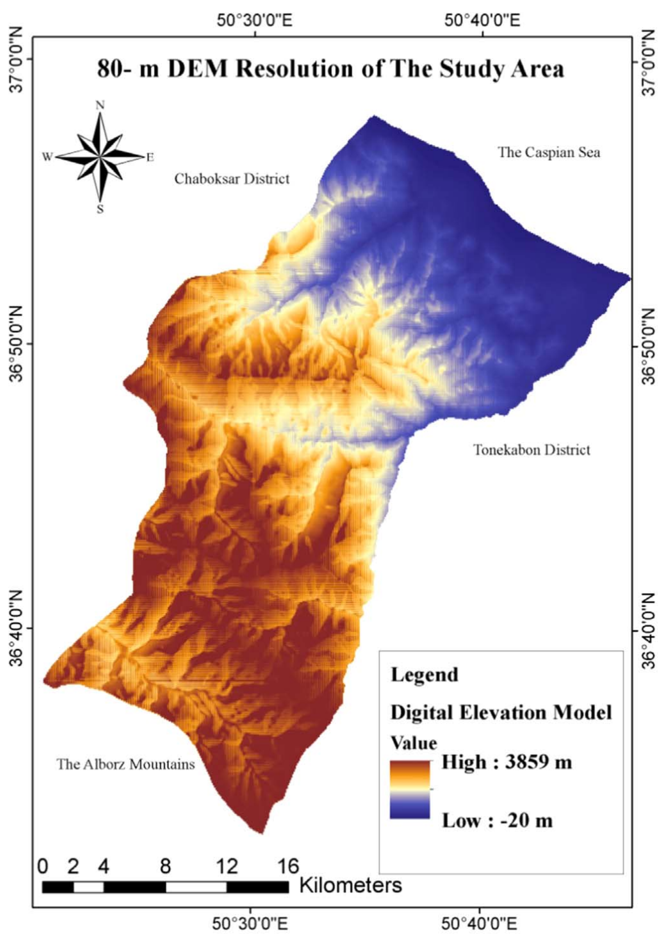

Fig. 3. Digital Elevation Model (DEM) of the study area.

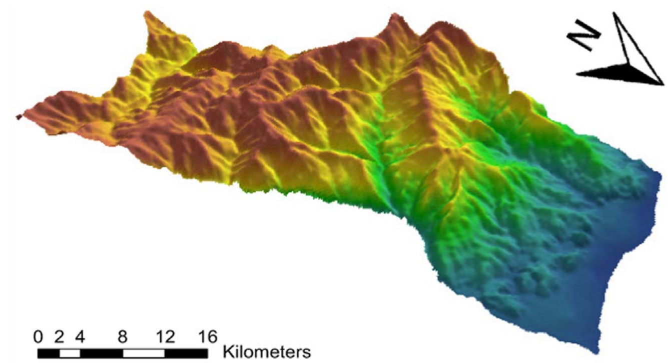

Fig. 4. 3D Digital Elevation Model (DEM) of the study area.

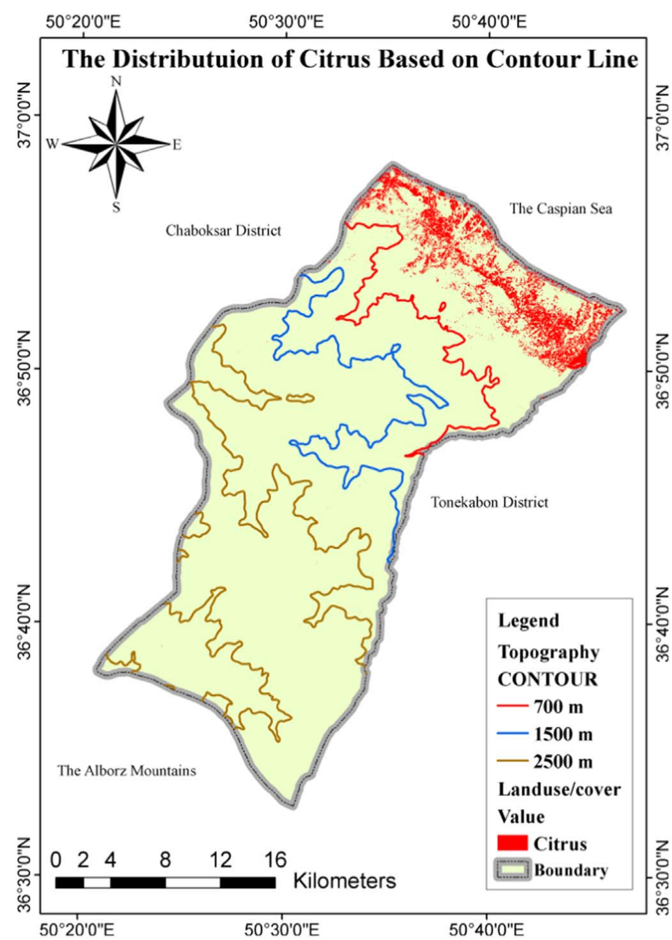

Fig. 5. The spatial distribution of citrus orchard in the study area in 2013.

from 5% of the area in 2003 to 10% in 2013.

It is necessary to know the variables that are relevant to the geographical patterns especially the climatic variables namely minimum temperature and altitude. Our analysis suggests that within the Ramsar region, the optimum citrus producing zone could need to shift upward altitudinally by 200–300 m in the northern highlands.

These result confirm those of (Huang et al., 2011) who showed that

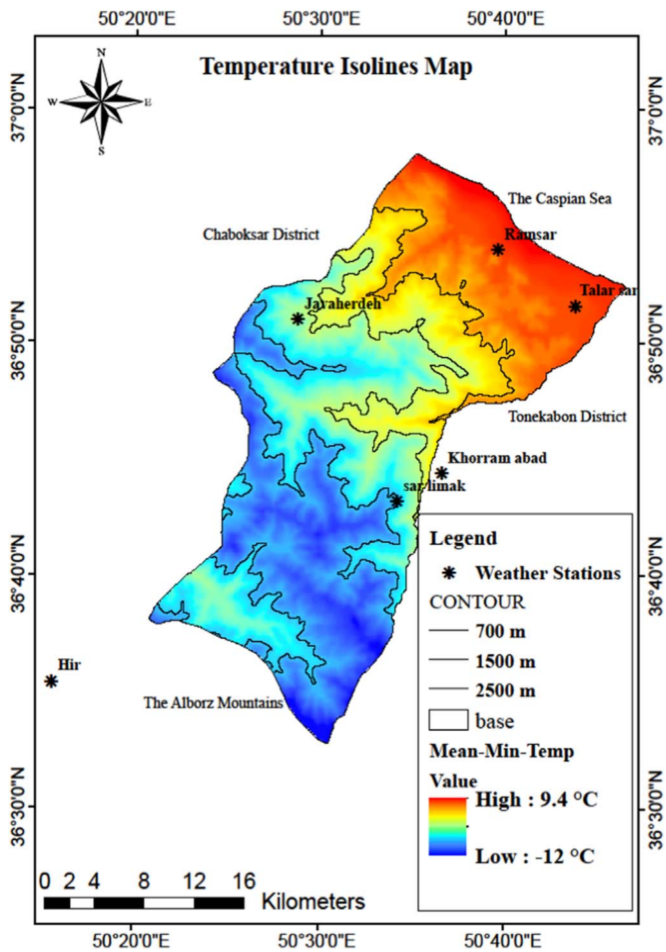

Fig. 6. The mean minimum temperature index map based on contour lines (scale: 1:50,000).

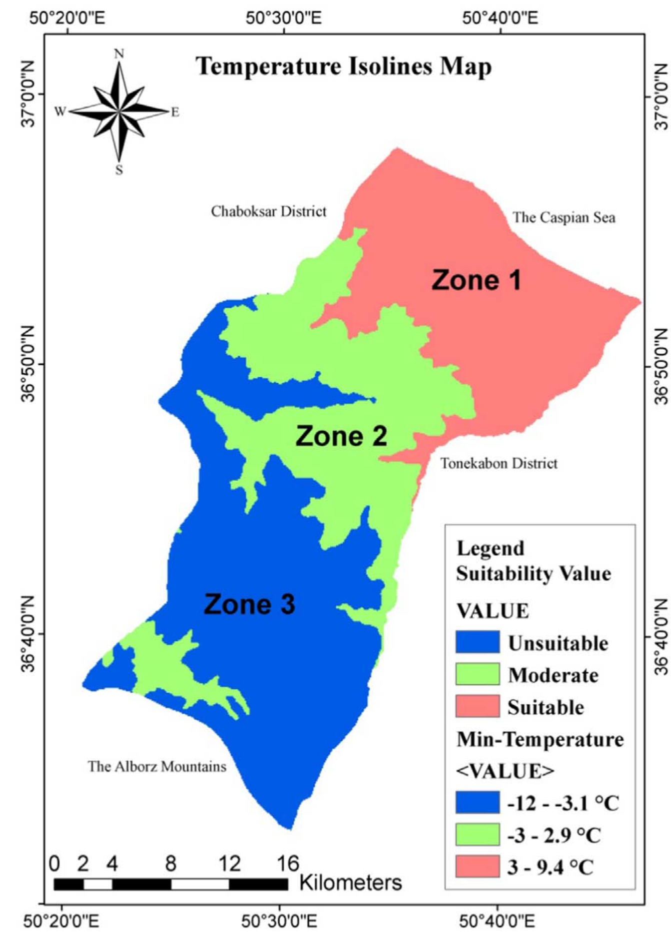

Fig. 7. The classified citrus growing regions within three agro-ecological zones in Ramsar district (scale: 1:50,000).

low temperature and the high elevation significantly affected woody plants like citrus growth and causes yield losses. Within the fruiting stage of maturity, the ripening stage in January and February was found to be the most susceptible stage for citrus crop yield associated with high FS. Overall, the results have clearly proven a remarkable sensitivity of late-autumn, winter-harvest in terms of FS. These severe climate disrupt cropping conditions in production areas and result in geographical shifts of some insensitive species such as apple (*Malus domestica* Borkh.), persimmon (*Diospyros kaki*, L.) and kiwifruit (*Actinidia deliciosa)*. Replacing them by introducing new fruit crops and/or varieties with low chilling and heat requirements could be a way of adaptation to climatic constraints.

5. Conclusions

A number of studies have evaluated the performance of statistical analysis associated with crop production, though few reported on the combination of GIS technique with linear regression on citrus orchards at a regional scale. The present study showed that differences in altitudes, based on DEM data, and associated FS in responses to maturity stages have profound influence on the citrus production and geographical distribution in Ramsar district. The climatic information is important to support citrus orchards distribution and help growers to refine their current orchards management activities. It could provide prevention for citrus investment and development in high-risk areas in the context of FS. The analysis although suggests that it would still be possible to increase citrus cultivation to 700 m (boundary of zone 1 & 2) in the study area. It may be crucial to design climate-smart practices and adaptation strategies in citrus less suitable region (zone 2).

This study found that both minimum temperature and altitude have a significant impact on citrus spatial distribution. In addition, these relationships reinforce the notion that the decreasing minimum temperatures have a significant influence during the repening phases, which means that zone 2 and 3 are in restricted regions in relation to citrus production. Interestingly, the frequency of climate extreme events especially FS which are conicide with harvesting time of citrus crops are inevitable in zones 1, 2 and 3. The novel and more applicable of linear regression suggest the observed and estimated value with a greatest correlation.

However, despite the differences between citrus cultivars in response to freezing tolerance and thus threshold of elevation, this parameter always had negative impacts on citrus trees in mountainous regions. Late maturing citrus varieties which performed sensitive and poorly during the critical month of January and February were judged unsuitable to southern regions (uplands). Sour orange (*Citrus aurantium* L.) as a tolerant grafted species has been suggested as being preferable due to a more consistent cropping pattern. Late blooming cultivars would show more unstable blooming dates due to concidence with freezes damage during December, January and February. This finding revealed that the application of climatic factors in particular low temperature due to FS in moderate areas are the most serious threats to commercial citrus crop production. To strengthen the confidence and relevance of our findings, it would be valuable if similar analyses were to be conducted in other citrus growing countries.

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