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Prediction models for frost / low-temperature stress in subtropical fruit plantations

Shashi Kumar Sharma
Dr. Y.S. Parmar University of Horticulture and Forestry
Institute of Biotechnology and Environmental Science, Neri
P.O. Khagal, Distt. Hamirpur - 177001, India
E-mail: shashi_uhf@yahoo.com

ABSTRACT

During winters, frost is a phenomenon of common occurrence in subtropical lower Himalayan region. In the recent past, it has caused considerable economic losses to fruit growers. Recommendations for protection against frost do exist, but benefits to orchards are rare due to lack of information on the level of low temperature these crops may experience in a frosty event. Studies have been conducted at Regional Horticultural and Forestry Research Station, Neri, Hamirpur, Himachal Pradesh on development of prediction models for minimum temperature and temperature-evolution during a frost event. Variables like sunset-time temperature, temperature drop and humidity increase from sunset time until two hours, have been found to explain about 74% of the total variation observed in minimum temperature. Evolution of temperature during a frosty night showed that temperature drop after sunset was an inverse exponential function of time after sunset. It justified about 67% of the total variation in temperature-evolution trend. Thiel's inequality coefficient for predicted versus actual values indicated good to very good forecasting performance of the regression lines developed. Further decomposition of inequality into bias, variance and covariance proportions also supported fitness of these lines for future prediction. Based on the information generated, a grower-friendly frost protection guide-chart (S-chart) has been developed. The chart provides information on intensity and duration of temperature below the critical level of damage for different fruit species. It also serves as a guide for the level of protection needed and for automation of protection methods against frost and low temperature damage.

Key words: Minimum temperature forecasting, temperature evolution, forecasting performance, S-chart

INTRODUCTION

Despite tremendous advances made in agriculture, agrarian output remains weather and climate dependent. Frost or low temperature stress is the single, weather-related phenomenon causing losses greater than any other environmental or biological hazard. Frost induced freezing is one of the severest stresses as, it causes ice formation, dehydration and cell deformation leading to an irreversible condition leading to death or malfunction of plant cells. Major causes of damage to subtropical fruit species are excessive cooling of the plant surface and subsequent freezing of inter- or intra-cellular water. As plants are immobile, they face certain stress under natural conditions. To withstand freezing, cold-hardy plants have developed mechanisms to regulate ice formulation in their tissues. But, subtropical plants lack this intrinsic defense mechanism against frost or low temperature. Even when all other aspects of crop production are well-managed, just one night of sub-zero temperatures can lead to complete crop loss in many subtropical fruit species (Snyder and Melo-Abreu, 2005). Quantum of damage caused depends mainly on how fast temperature drops and to what extent the plant supercools before freezing (Pearce, 2001).

Lower Himalayan region has been classified as subtropical (Thornwaite, 1948), but, repeated occurrence of frost during winters renders the region sub-optimal for growing subtropical fruit. In winters, these fruit species usually experience freezing situation due to reduction in sensible heat content of the air (net energy loss through radiation from the surface to the sky, i.e., radiation frost) near the plant surface. To prevent damage to fruit plantations due to frost-induced freezing several protective measures are recommended such as, wetting of plant or soil surface, fogging with water or thermohysteric compounds or covering technique using plastic, paper or foam (UHF, 2010). For effective application of protection systems against lethal damage, reliable prediction of intensity and duration of frost is necessary. Weather services, to which the general public has considerable access, are quite broad and generalized as these use synoptic and/or meso-scale models for regional forecasts. Local or micro-scale predictions are typically unavailable. Therefore, empirical predictions that can be calibrated for local conditions are urgently needed. It is clear that in the years to come, climatic variability will play an even greater role than in the past, and precise prediction of low temperature will be, greatly significant. Therefore, to facilitate decision-support system on 'if and when' frost protection is needed, the present studies were designed so as to develop an effective forecasting methodology against frost or low temperature stress.

MATERIAL AND METHODS

The studies were conducted in subtropical lower Himalayan region at three high-frost prove locations having geographic coordinates as: i) 31°40'07" N, 76°34'46" E, Altitude 950 masl, ii) 31°41'44" N, 76°21'52" E, Altitude 605 masl and iii) 31°54'32" N, 76°17'06" E, Altitude 523 masl. Automatic Temperature and Humidity Recorder (MADGE-TECH, RHTemp101) was installed at these locations for continuous data recording during winters of 2008-09, 2009-10 and 2010-11. Prediction of minimum temperature (T_{dip}) during a radiation frost event was made on the basis of the following explanatory variables:

i. T_{max} - highest temperature (°C) recorded during day-time

ii. T_{530} - temperature (°C)recorded at sunset (5:30PM)

iii. TD_{5630} - temperature drop (°C) within one hour after sunset

iv. TD_{5730} - temperature drop (°C) within two hours after sunset

v. RH_{min} - minimum relative humidity (%) recorded during day-time

vi. RH_{530} - relative humidity (%) recorded at sunset

vii. RHd_{5630}- increase in relative humidity (%) within one hour after sunset

viii. RHd_{5730}- increase in relative humidity (%) within two hours after sunset

Data for all locations and years were pooled and analyzed as per Gupta and Kapoor (1976). Minimum temperature observed (T_{dip}) during a radiation frost event was confidened a dependent variable, whereas, the other variables (individually or in combination) were taken as explanatory variables. Mathematical measure of average relationship between dependent and explanatory variables, in terms of original units of data, was obtained by the principle of least squares (Gupta and Gupta, 1996). Prediction line for temperature at different levels of time (T_i) during a frost event, i.e., temperature-evolution after sunset, was derived by different polynomial fitting procedures for obtaining the line of best fit. It was factored-in as time-defined drop in temperature after sunset until the next morning at 7:30 AM. All the curve-fitting was done using SPSS and SX statistical packages.

Significance of the regression coefficients was tested by standard t-test and overall significance of regression was tested using F-test. Coefficient of determination (Adjusted R^2) was taken as the criterion for selecting suitable regression or prediction line. To test the significance of discrepancy between theory (predicted values) and experiment (actual values), chi square (χ^2) test of goodness of fit was applied. Further, forecasting performance of the prediction models was judged through prediction realization diagram as per Theil (1966) and Koutsoyiannis (1991). A systematic measure of accuracy of the prediction model was obtained through Theil's inequality coefficient, which was decomposed into bias, variance and covariance proportions of partial inequality, for insight into sources of prediction errors.

Observations were also recorded on actual level of damage to fruit plantations at experimental sites. Twenty per cent damage to the foliage was considered critical, beyond which effective frost protection was deemed necessary. For devising frost protection guide chart, polynomial curve fitting was done with reference to sunset time temperature, and temperature evolution after sunset. Frost protection guide chart was developed for very sensitive, sensitive or less sensitive fruit species as defined by Badiyala (2008) and Sharma (2011). The chart so developed was designated as 'Shashi's chart or s–chart'.

RESULTS AND DISCUSSION

Descriptive statistics of various temperature and humidity related variables are presented in Table 1. Minimum temperature (T_{dip}) during a frost event varied from -0.8°C to 3.2°C. Confidence limit of this variable indicates that for most of the frost events, minimum temperature was between 1.0°C to 2.33°C. During the period of study, maximum day temperature ranged from 13.5°C to 15.3°C. Sunset time temperature was recorded as 7.1°C, to 12.8°C with average value of 10.9°C and confidence limit of 9.5°C to 10.3°C. After sunset, the temperature dropped to between 0.40°C

Table 1. Descriptive statistics of variables during radiation frost events

Variable	Minimum	Maximum	Mean	Confidence limit
T_{dip}	-0.80	3.20	1.03	1.00 - 2.33
T_{max}	8.90	17.80	13.90	13.50 - 15.30
T_{530}	7.10	12.70	10.90	9.50 - 10.30
TD_{5630}	0.40	3.30	2.07	1.89 - 2.25
TD_{5730}	0.60	5.90	3.48	3.18 - 3.78
RH_{min}	35.50	65.20	50.00	48.10 - 52.90
RH_{530}	46.00	72.30	67.40	43.10 - 48.90
RHd_{5630}	10.00	26.00	19.22	12.00 - 22.45
RHd_{5730}	16.00	36.00	24.70	20.30 - 32.90

Table 2. Regression lines for prediction of minimum temperature during a radiation frost event

Regression line No.	Regression line	R^2	Adj. R^2	F_{cal} (0.05)
1.	T_{dip}=-2.06+0.285 (T_{530})*	0.5556	0.5155	*
2.	T_{dip}=-1.86+0.426 (T_{530})*-0.499 (TD_{5730})*	0.6593	0.6141	*
3.	T_{dip}=-1.63+0.368 (T_{530})*-0.558 (TD_{5730})* +0.041 (RHd_{5730})*	0.7518	0.7374	*

*Significant at 5% level

and 3.30°C within an hour. Average drop was about 2.1°C. For a majority of frost events, this drop was within the confidence limit of 1.89°C to 2.25°C. Within two hours, temperature drop after sunset was between 0.60°C to 5.90°C, with average drop of 3.48°C. Confidence limit for this variable was 3.18°C to 3.78°C. Minimum relative humidity in a day ranged between 35.5% and 65.2% whereas, at sunset-time, it ranged between 46% and 72.3%. Confidence limit for these variables was 48.1% to 52.9% and 43.1% to 48.9%, respectively. Within the hour increase in humidity after sunset was recorded at 10 to 26% and within two hours increase ranged between 16% and 36%. Confidence limit of this variable was within 20.3% to 32.9%.

Prediction of minimum temperature during a frost event

Minimum temperature during a frost event (T_{dip}) was regressed upon the above-described variables one by one, or in different combinations Regression lines with significant coefficients of independent variables are presented in Table 2. From line 1, it is evident that sunset time temperature (T_{530}) explained around 52 % of the total variation in minimum temperature (T_{dip}) during a radiation frost event. This variation in the dependent variable (T_{dip}) could explain upto 61% (regression line 2) when temperature-drop upto two hours after sunset (T_{5730}) was considered along with sunset temperature (T_{530}). Incorporation of increase in humidity at two hours after sunset (RHd_{5730}) as an additional explanatory variable, further improved the value of adjusted R^2 to 74% (regression line 3). This implies that temperature at sunset, drop in temperature and increase in relative humidity within two hours of sunset significantly influenced minimum temperature of a forthcoming frost event. These variables have been found to explain around 74% of the total variation in minimum temperature during this event. Gaussian identification procedure developed by Krasovitski *et al* (1996) also emphasized that temperature drop rate after sunset definitely determines minimum temperature of a frost event. Reports on correlation of minimum temperature with increase in relative humidity after sunset in combination with sunset time temperature are rare.

Prediction of temperature evolution after sunset during a radiation frost event:

Among the polynomial expressions tested, the following inverse exponential curve (regression eq. 4) defined temperature at i^{th} hour after sunset, with highest value of coefficient of determination (adjusted R^2) taking hours after sunset (i) and sunset time temperature (T_{530}) as

$$T_i = T_{530} - (0.27 * T_{530} * i)/e^{(o.1*i)}$$

…..(Adj. R^2 =0.6745) …Reg. Eq. (4)

$\int_0^{14}$ i = hours after sunset {at sunset/5:30PM i=0, at sunrise/ 7:30AM i=14}

T_i = Temperature at i^{th} hour after sunset

$\int_7^{13} T_{530}$ = Temperature at Sunset (5:30 PM)

explanatory variables. This equation explained that temperature dropped after sunset as 0.27^{th} of the product of T_{530} and $1/10^{th}$ inverse of exponential progression of time after sunset, i.e., (i). These explanatory variables explained about 67% of the total variation in the trend of temperature-evolution during a frost event. Krasovitski *et al* (1996) also asserted that pre-night period air temperature played a vital role in temperature evolution during the night. Snyder and Melo-Abreu (2005) suggested updating night temperatures by taking pre-night temperature as the reference when predicting air-temperature trend during a frost event. They demonstrated that air temperature trend calculation used a square root function from two hours after sunset, until sunrise the next morning.

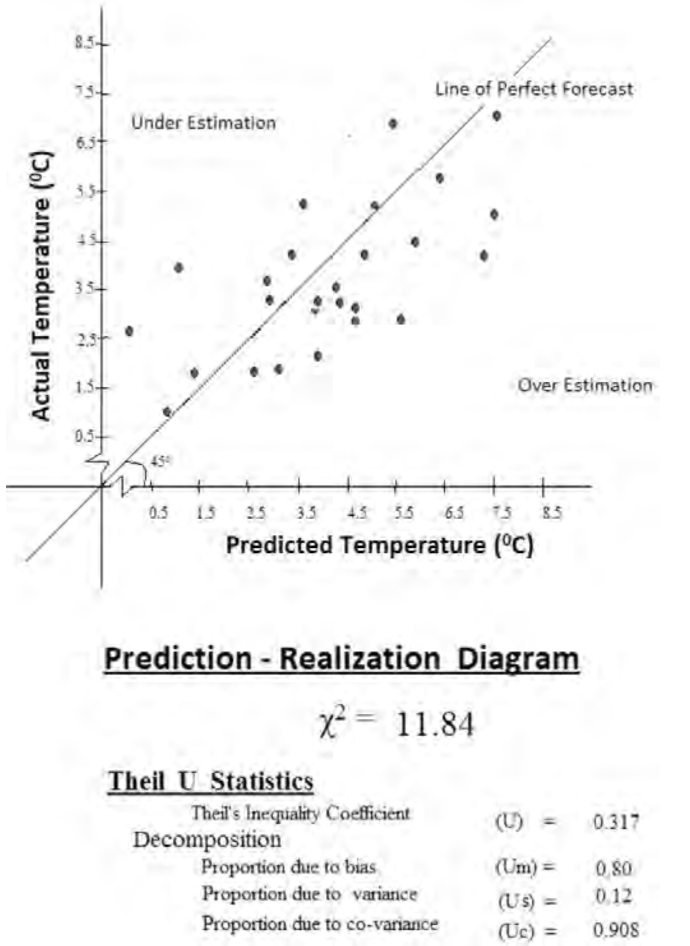


Fig 1. Evaluation of prediction performance of estimated regression line 3

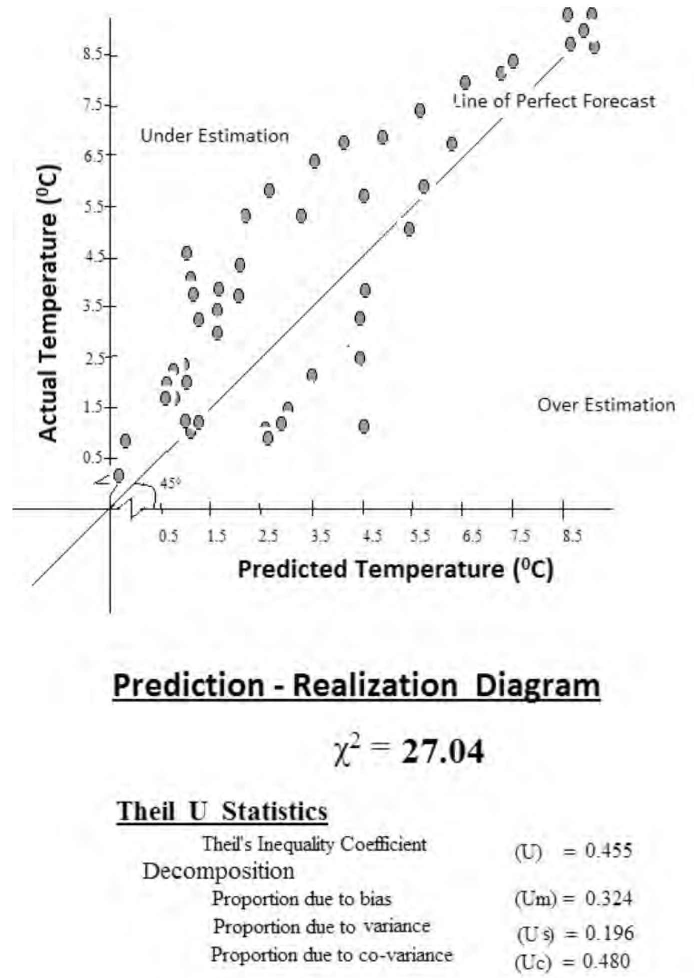
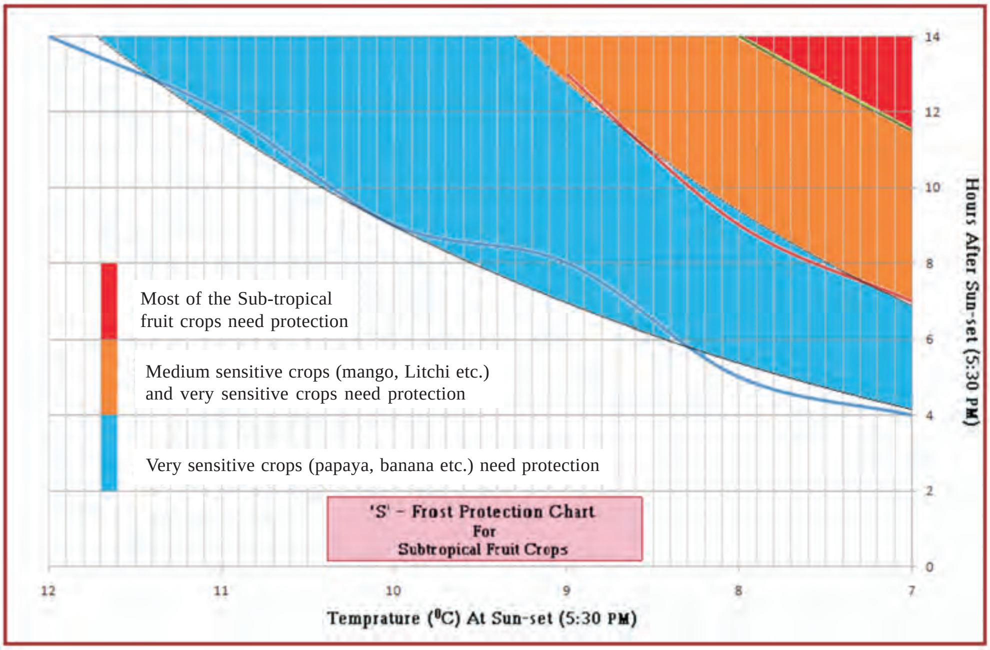


Fig 2. Evaluation of prediction performance of estimated regression line

Evaluating forecasting performance of prediction models

Regression line 3 with highest coefficient of determination (adjusted R^2) and highest number of significant explanatory variables were considered as prediction models for minimum temperature of a frost event. Forecasting performance of this line has been represented through 'Prediction–Realization Diagram' presented in Fig 1. Which shows that distribution of the points of predicted versus actual values of minimum temperature are well distributed around the line of perfect forecast. The χ (11.84) calculated is lower than the tabulated value of $\chi_{(0.05,\ 25)}$, and signifies acceptance of regression line 3 for predicting the minimum temperature of a radiation frost event at 5% level of significance. Further, 'Theil's Inequality Coefficient' (U=0.317) also indicates that as per Sharma and Julia (1996) scale, regression line 3 depicts very good forecasting performance to judge its ability as a forecasting model. Partial coefficients of inequality indicated that the major contribution to inequality existing during forecasting performance evaluation was due to imperfect covariance (Uc =0.908). The systematic errors (Um and Us) contributed very little to the inequality.

Prediction and realization diagram of regression line 4, i.e., forecasting model for estimating temperature-evolution after sunset during a radiation frost event, is presented in Fig 2. The points for predicted versus actual values were well-oriented around the line of perfect forecast. Majority of the points figured in the under-estimation zone, but value of χ (27.04) was found to be less than the tabulated value $\chi_{(0.05,\ 49)}$ which indicated that regression line 4 was acceptable at 5% level of significance



for prediction of post-sunset temperature-evolution during a radiation frost event. Theil – U (0.455) also indicated good forecasting ability of the line as per the Sharma and Julka (1996) Scale. Partial coefficients of inequality indicated that inequality existed mainly due to imperfect covariance (Uc) and unequal central tendency (bias proportion, Um).

From a forecaster's stand-point, if the total inequality coefficient (U) cannot attain the desirable level 0, the most desirable level of Um is H"0. The same is expected for inequality due to imperfect covariance (Uc). As predictions are rarely equal to actual outcomes, this type of error is of the non-systematic type. If Us'"0, this might be called 'systematic' and is due to forecaster's neglect (Theil, 1962 and 1966). Distribution of inequality of line 3 is very close to desirable distribution, i.e., UmH" UsH" 0 and UcH"1; thus, it has greater level of acceptance as a model for prediction of low temperature during a frost event. Regression line 4 also possessed good forecasting performance, but the value of Uc was a bit farther from 1, which indicates that forecasting performance of this line stands to be improved further in future with incorporation of more information into the forecasting process.

Frost protection guide chart

The 'S–chart' presented below depicts that sunset time temperature below 11.7^{o}C was critical for 'very sensitive' fruit crop species, as, whenever this situation prevailed, over 20% damage to foliage was observed. Hence, it can be inferred, that, very sensitive crops should be given protection against frost whenever sunset time temperature goes below 11.7^{o}C. Duration for which this protection is needed will be higher for lower temperatures. Medium sensitive crops like mango and litchi were affected (>20% foliage damage) only when sunset-time temperature was below 9.3^{o}C. When this was below 8^{o}C, almost all the crops were affected by frost. Further, it is depicted in the chart that when the sunset-time temperature is 10^{o}C, sensitive crops will need protection after about eight and half hours after sunset, i.e., after 1:30AM in the night; these plants will need protection for the next four and half hours. Similarly, if the sunset-time temperature is 8^{o}C, the sensitive and medium-sensitive crops will need protection. The sensitive crops will need protection from after about four and half hours after sunset, whereas medium sensitive crops will need protection after eight and half hours after sunset, i.e., after 1:30AM (protection for the next four and half hours). Thus information presented in the chart may be utilized for automation of frost protection systems. (e.g. if you have a mango orchard, programme the frost protection system to get operational at 1:30 AM whenever sunset-time temperature is below 8^{o}C. If this temperature is above 9.3^{o}C, do not bother to get the system operational). In general, it can be speculated that growers of sensitive crop should be at alert whenever sunset time temperatures start sliding below 11.7^{o}C. Along with growers of sensitive crop, growers of medium sensitive fruit crops too should be cautions whenever sunset-time temperatures go below 9.3^{o}C. When sunset time temperature goes below 8^{o}C, all fruit growers should be at alert for frost protection of their crop. Method of protection to be adopted can also be opted for on the basis of duration for which protection is needed. In a similar study, Krasovitski *et al* (1996) used earth surface-temperature as a guide for optimal application of frost protection methods.

From the above results, it is concluded that frost is a phenomenon of common occurrence in the lower subtropical Himalayan region of Himachal Pradesh, and sub-zero temperatures are not uncommon here. Minimum temperature of frost event may be predicted well on the basis of sunset time temperature, temperature-drop and humidity increase within two hours of sunset. Evolution of temperature during a frosty night may be predicted with sufficient accuracy on the basis of sunset-time temperature. Further, frost protection guide chart can be used for assessing the level of protection needed for a target crop at various sunset-time temperatures. Automation of frost protection methods can also be facilitated with help of this guide chart.

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REFERENCES

Dunn, E. 2010. How to use water mist to reduce frost damage to fruit trees. www.ehow.com/how_5805520

Fuller, M.P. and Wisniewski, M. 1998. The use of infrared thermal imaging in the study of ice nucleation and freezing in plants. *J. Thermal Biol.*, **23**:81-89

Ge, X. and Wang, X. 2009. Estimation of freezing point depression, boiling point elevation and vaporization enthalpies of electrolyte solutions. *Ind. Engg. Chem. Res.*, **48**:2229-2235

Groenzin, H., Li, I. and Shultz, M.J. 2008. The single crystal basal face of ice - investigating with sum frequency generation. *The J. Chem. Phy.*, **128**:214510

Gupta, C.B. and Gupta, V. 1996. Tests on small samples and goodness of fit. **In**: An Introduction to Statistical Methods (20th Revised Ed.). Vikas Publishing House Pvt. Ltd., New Delhi 781p.

Gupta, S.C. and Kapoor, V.K. 1995. Fundamentals of Mathematical Statistics. (9th Edn.), Sultan Chand and Sons, New Delhi, India, pp. 3.1-3.15

Gusta, L.V., Wisniewsky, M. Nesbitt, N.T. and Gusta, M.L. 2004. The effect of water, sugars and proteins on the pattern of ice nucleation and propagation in acclimated and non acclimated canola leaves. *Pla. Physiol.*, **135**:1642-1653

Hollis, J.M., Lovas, F.J., Jewell, P.R. and Coudert, L.H. 2002. Interstellar antifreeze: Propylene Glycol. *The Astrophy. J.*, **571**:L59-L62

Koutsoyiannis, A. 1991. Testing the forecasting power of an estimated model. **In:** Theory of Econometrics (2nd Ed.), ELBS with Mac Millan pp. 165-171

Laporta, N., Zacchini, M., Bartolini, S., Viti, R. and Roselli, G. 1994. The frost hardiness of some clones of olive cv. 'Leccino'. *J. Hortl. Sci.*, **69**:341-345

Mancuso, S. 2002. Electrical resistance changes during exposure to low temperature measure chilling and freezing tolerance in olive tree (*Olea europea* L.) plants. *Pl., Cell and Environ.*, **23**:291-299

Pearce, R.S. 2001. Plant freezing and damage. *Ann. Bot.*, **87**:417-424

Sakai, A. and Larcher, W. 1987. Frost survival of plants: Responses and adaptation to freezing stress. **In**: Ecological Studies., **62**. Springer- Verlag, Berlin

Snyder, R.L. and Melo-Abreu, J. Paulo, de. 2005. Frost protection: Fundamentals, practice and economics. FAO, **In**: *Envir. Natural Resource Series,z* **10**:1-12

Soleimani, A. Lessani, H. and Talaie, A. 2003. Relationship between stomatal density and ion leakage as indicators of cold hardiness in olive (*Olea europea* L.). *Acta Hort.*, **618**:521-525

Theil, H. 1962. Economic Forecast and Policy. North Holland. Pp. 1-48

Theil, H. 1966. Applied Economic Forecasting. North Holland. Pp. 26-36

Thornwaite, C.W. 1948. An approach towards a rational classification of climate. *Geograph. Rev.*, **38**:55-94

UHF. 2010. http://www.yspuniversity.ac.in/package/pack-fruitcrops

Wisniewski, M., Fuller, M., Glenn, D.M., Palta, J., Carter, J., Gustta, L., Griffith, M. and Duman, J. 2001. Factors involved in ice nucleation and propagation in plants: an overview based on new insights gained from the use of infrared thermography. *Buvisindi –Icel. Agril. Sci*., **14:**41-47

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