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A web-based fuzzy expert system for frost warnings in horticultural crops

Robert F. Chevalier[a,1], Gerrit Hoogenboom[a,b,*], Ronald W. McClendon[a,c], Joel O. Paz[b,2]

[a] Institute for Artificial Intelligence, the University of Georgia, Athens, GA 30602, United States
[b] Department of Biological and Agricultural Engineering, the University of Georgia, Griffin, GA 30223, United States
[c] Department of Biological and Agricultural Engineering, the University of Georgia, Athens, GA 30602, United States

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ABSTRACT

Frost damage is responsible for more economic losses than any other weather related phenomenon in the United States (USA) and many other regions across the globe. With sufficient warning, producers can minimize the potential damages caused by frost and freeze events. However, the severity of these events is dependent upon several factors including air temperature, dew point temperature, and wind speed. Methods for assessing this risk are not easily quantifiable and require the insight of experts familiar with the process. **G**eorgia's **E**xtreme-weather **N**eural-network **I**nformed **E**xpert (GENIE) incorporates the knowledge of expert agrometeorologists and additional information on air temperature, dew point temperature, and wind speed into a fuzzy expert system for use by Georgia producers to provide warning levels of frost and freeze for blueberries and peaches. Artificial neural network (ANN) predictions of air temperature and dew point temperature across the state of Georgia for one to 12 h ahead and observed wind speed are used as input variables for this fuzzy expert system. Meteorological conditions were classified into five levels of frost and freeze by the expert agrometeorologists. These expertly classified scenarios were then used to develop fuzzy logic rules and membership functions for GENIE. Additional scenarios were presented to GENIE for evaluation and it classified all scenarios correctly. This tool will be made available to Georgia producers through a web-based interface, which can be found at www.georgiaweather.net.

1. Introduction

Agricultural crops in many geographical regions of the U.S. are susceptible to damage from frost and freeze events during the growing season (White and Haas, 1975; Rodrigo, 2000). For instance, in the state of Georgia a freeze occurred in early April of 2007 that resulted in estimated losses of 50% of the peach crop and 87% of the blueberry crop (Fonsah et al., 2007). The 2007 Georgia Farm Gate Value Report (Boatright and McKissick, 2008) noted that the values for fruits and nuts for 2007 were down by $65 million compared to the previous year as a result of this late freeze event. These types of damages can be mitigated with preventative measures such as irrigation and orchard heaters, provided that producers are given sufficient notice of impending frost and freeze events.

Frost events are classified based on the particular atmospheric conditions causing the loss of heat. Radiation frosts occur when heat is lost through radiation, causing the warm air close to the surface to be inverted with the colder air in the atmosphere. These frosts are characterized by clear skies, no wind, and a low dew point temperature. Advective frosts occur when wind brings cold air into a region replacing warmer air. Advective frosts are characterized by cloudy skies, moderate to strong winds, no temperature inversion, and low humidity. It is generally accepted that a frost event becomes a freeze event when extracellular water within a plant freezes. Freeze events are particularly damaging to crops because this extracellular ice formation draws water out of plant cells and causes dehydration that can ultimately result in permanent tissue damage (Rodrigo, 2000; Snyder and de Melo-Abreu, 2005).

The National Weather Service (NWS), the main provider of weather forecasts in the USA, currently issues three levels of frost and freeze warnings (Perry, 1994). A *frost* warning is issued when forecasts call for air temperatures near, but not below 0 °C and wind speeds below 16 km/h. A *frost/freeze* warning is issued when forecasts call for air temperatures below 0 °C and wind speeds below

* Corresponding author. Current address: AgWeatherNet, Washington State University, Prosser, WA 99350. Tel.: +1 509 786 9371; fax: +1 509 786 9370.
E-mail address: gerrit.hoogenboom@wsu.edu (G. Hoogenboom).
[1] Current address: Lockheed Martin Advanced Technology Laboratories, Cherry Hill, NJ 08002, United States
[2] Current address: Department of Agricultural and Biological Engineering, Mississippi State University, Mississippi State, MS 39762, United States

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16 km/h. Finally, a *freeze* warning is issued when forecasts call for air temperatures below 0 °C and wind speeds greater than 16 km/h. While the NWS warnings take into account air temperature and wind speed, they do not consider the dew point temperature. Additionally, there is little granularity in the NWS warnings since there are only three distinct warnings issued. The utility of the NWS warnings for Georgia producers is further limited by the fact that the NWS focuses on urban areas and does not collect weather data from many of the rural areas where agricultural production is prevalent.

The Georgia Automated Environmental Monitoring Network (AEMN) was created for the purpose of collecting weather data from areas across the state of Georgia, especially for those regions where the NWS does not have a presence (Hoogenboom, 1993). The AEMN consists of over 80 stations whose data are disseminated in near real-time via the AEMN website (www.georgiaweather.net). The data from each weather station are downloaded to a central computer every 15–60 min, using a combination of dedicated land lines, cell phones, and the internet. The data are processed once they are received and then pushed to the web-server. Using data collected from AEMN stations, Artificial Neural Network (ANN) models were created to predict air temperature (Jain et al., 2006; Smith et al., 2006, 2009) and dew point temperature (Shank et al., 2008a, 2008b). Smith et al. (2009) developed twelve ANN models to predict the air temperature one- to 12-h ahead for year-round conditions in Georgia. These models incorporated the feedforward backpropagation algorithm for training. Inputs to the models included AEMN prior hourly weather data for a 24-h period. Model development and evaluation datasets were created such that there was no overlap of weather station locations or years of data. Using independent weather data from the evaluation set, the mean absolute error of the prediction ranged from 0.516 °C for a 1-h prediction to 1.873 °C for a 12-h prediction. Shank et al. (2008a, 2008b) developed ANN models to predict hourly dew point temperatures for periods of one- to 12-h ahead. Again, the available AEMN data were partitioned so that independent datasets were used for training and evaluation. The mean absolute error of the prediction for the evaluation dataset ranged from 0.550 °C for a 1-h prediction to 2.281 °C for a 12-h prediction. The 24 ANN models predicting air temperature and dew point temperature for the subsequent 12 h are available online for any of the 80+ AEMN weather sites. These predictions are generated every 15 min as new data are downloaded to the AEMN server. Support Vector Machine (SVM) models were also developed to predict air temperature using the same datasets. A comparison of the accuracy of these SVM models with the accuracy of the ANNs was performed by Chevalier et al. (2011).

Given the proximity of the weather stations to Georgia's croplands, the ANN predictions of air temperature and dew point temperature provide valuable information to producers across the state. However, considerable agrometeorological expertise and experience are necessary to be able to translate these temperature predictions and observed wind speed values into the levels of threat, due to frost and freeze, for particular crops. A natural extension to the provided temperature predictions would be to interpret these predictions for use in a frost and freeze event decision support system.

Fuzzy Logic is derived from Fuzzy Set theory and is a superset of the more conventional Boolean Logic (Zadeh, 1965). Fuzzy Logic is a method of reasoning that allows for information that is approximate, rather than precise. It is based on fuzzy sets as opposed to the two-valued sets which are the basis of Boolean Logic. In both forms of logic, the membership of an input variable in a given set can be determined by applying a membership function to the input. In Boolean logic, there are only two possible outputs: a zero, which signifies that the input variable is not a member of the set, or a one, which signifies that the input variable is a member of the set. In Fuzzy Logic, partial membership in a set is possible because output values can be any number in the continuous set [0, 1]. The output value assigned by a fuzzy membership function, therefore, represents the degree to which an input is a member of the set. The process of applying a fuzzy membership function to an input variable is referred to as "fuzzifying" the "crisp" input value (Engelbrecht, 2002). These fuzzy inputs are then used to define fuzzy if-then rules, and ultimately, to produce crisp output values. Formally implementing fuzzy logic involves the following five steps: fuzzification of the inputs, application of fuzzy operators in the rule antecedents, implication from the rule antecedents to the rule consequents, aggregation of the consequents, and defuzzification to a crisp output value (MathWorks, 1999).

Expert systems, which are based on Fuzzy Logic, have proven useful in many domains including natural resource management (Nguyen et al., 2007) and meteorology. The MEDiterranean EXpert system (MEDEX) was developed to predict specific gale-force wind events in the Mediterranean Sea (Hadjmichael et al., 2002). The inputs were supplied by various numerical models and the predictions of this expert system were shown to be competitive with those produced by the US Navy at its regional forecasting center in Rota, Spain. The Significant Information Generated from Marine Area Reports (SIGMAR) system was used to alert meteorologists when the accuracy of their marine forecasts began to deteriorate (Hansen, 1997). In this application, a fuzzy expert system was used for diagnostic rather than predictive purposes. More traditional expert systems have been used to provide frost related decision support. Takle (1990) used an expert system to predict the occurrence of frost on bridges and roadways. The expert system relied upon maximum and minimum recorded temperatures from the previous day as well as several estimated variables which included cloud cover, air temperature, dew point temperature, precipitation, and average wind speed. These estimated variables were not produced by a numerical model. Rather the user of the expert system was expected to estimate these values. Similar work was performed in which a model for frost deposition on Iowa bridge ways was used as a decision support tool by providing it with predictions from an ANN (Temeyer et al., 2003). Inputs for this model included current air temperature, dew point temperature, wind speed, and surface temperature. With improvements in information and communication technologies and integration of various data sources, information for decision making can now be rapidly disseminated to potential users and stakeholders (Denzer, 2005; Hilty et al., 2006; Horsburgh et al., 2009; Smith and Lakshmanan, 2011) and it also provides new opportunities to make science and decision making more relevant (Liu et al., 2008).

The overall goal of the research reported herein was to develop a decision support tool to interpret predicted air and dew point temperatures and observed current wind conditions as frost and freeze event warnings related to blueberries and peaches for the subsequent 12-h period for any of the AEMN locations in Georgia. The specific objectives were: (1) to develop an expert system using fuzzy rules which encompasses the knowledge of expert agrometeorologists' published literature related to frost and freeze, (2) to verify the performance of the fuzzy expert system using additional weather scenarios not used in model development, and (3) to develop a web-based graphical user interface for disseminating the information to producers across the state of Georgia.

2. Materials and methods

A team of expert agrometeorologists was selected to provide the interpretation of current and predicted weather conditions as frost or freeze warning levels. The experts selected were Dr. Gerrit Hoogenboom and Dr. Joel Paz, both faculty members