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Predicting the incidence and severity of wheat aphids and development of a web-enabled forewarning system in India

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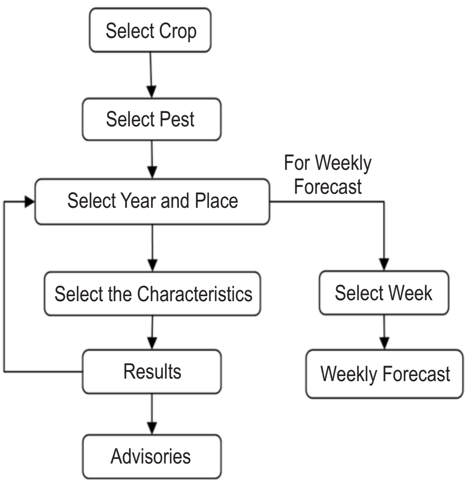
Abstract

Aim: Forecasting the incidence and severity of aphids, the major insect pest of wheat, is expected to significantly help in their management. In the present study, a set of weather-based models were developed to predict the timing and severity of *Rhopalosiphum maidis* infestation at Ludhiana falling under the North Western Plain Zone and *R. padi* at Niphad in the Peninsular Zone of India.

Methodology: The weather indices-based regression models for two locations, Ludhiana and Niphad, were developed using the aphid population and weather data gathered over eight years (2006–14), and the models' predictive accuracy was successfully tested over four additional years (2014-18). The developed statistical models were transformed into three-tier architecture, web-based system, i.e. Presentation, application and data tier for dissemination of information.

Results: The developed models can predict the crop's age - when aphids first colonize the plants, when the aphid population attains the peak and the information about the peak intensity of the aphid population. For predicting the crop's age at which population peaked at Ludhiana, the weighted interaction of the relative humidity (RH) in the evening and the number of hours of sunshine (NHS) along with the weighted interaction of minimum temperature and RH (morning) were important parameters while, at Niphad, the weighted NHS and the interaction of RH (morning and evening) were important. Likewise, for predicting the maximum aphid population at Ludhiana, the weighted interaction of minimum temperature and RH (morning) were important, while at Niphad, the key parameters were the weighted interaction of RH (evening) with the NHS.



Interpretation: A prototype system developed to forecast the location-specific (Ludhiana and Niphad) infestation of wheat crops by aphids is expected to facilitate aphid management through an accurate forewarning at the locations.

Key words: Mean Absolute Percentage Error, *Rhopalosiphum maidis*, *Rhopalosiphum padi*, Three-tier architecture, Weather-based regression model

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Introduction

Bread wheat is a staple crop in India, second only to rice in terms of its area cropped and its volume of production. Recently, various aphid species have been identified as pests in most of the Indian wheat-producing areas (Babu *et al.,* 2012). Of the 11 species reported to date, the corn leaf aphid, *Rhopalosiphum maidis* (Fitch) and the bird cherry oat aphid, *Rhopalosiphum padi* (Linnaeus) are the most common (Deol *et al.,* 1987). *R. maidis* is confined to leaf whorls only (Shekhar and Singh, 1999) whereas *R. padi* infests all above ground parts, but is predominant on leaves and stems. These two aphid species enjoy more or less cosmopolitan distribution and have been reported from different parts of India (Ghosh and Singh, 2002; Chander *et al.,* 2003; Kumar, 2014). However, *R. maidis* is the predominant species at Ludhiana falling under North Western Plain Zone, which is the most important wheat-growing zone of India contributing approximately 90% of the national buffer stock of wheat grains, while *R. padi* is major at Niphad falling under Peninsular Zone of the country. Though there can be instances when both species occur at the same time in a crop (Singh and Deol, 2003).

The population growth of these aphids is characterized by an initial slow build-up, followed by a phase of rapid multiplication, a slow decline, and a final collapse. The insects' ability to multiply so rapidly is a consequence of their asexual mode of reproduction (Shrivastava *et al.,* 2014). Aphids feeding on wheat plants not only weaken the plant directly but also promote the transmission of both viral and fungal pathogens (Khan *et al.,* 2012). Both nymphs and adults suck the sap from leaves and other parts of the plants wherever they infest (Patil *et al.,* 2014). The damage of aphids first starts from the periphery of the field, particularly on the side on which trees are present. Aphid infestation at different crop stages causes different kinds of damage. Due to the infestation of aphids in the early crop stage, root and shoot growth may be impaired as a result of aphids competing for nitrogen. Inadequate nitrogen for the crop may make the crop more vulnerable to the impact of an aphid infestation (Navarro *et al.,* 2020). The estimated extent of the losses to Indian wheat production resulting from aphid infestation ranges from 3-21% (Puri, 2000; Singh and Deol, 2003). No reliable sources of host resistance to aphid infestation have been identified so far, so the only effective means of managing them is by the well-timed application of appropriate insecticides (Singh *et al.,* 2018).

The efficacy of systemic insecticides is such that their usage is increasing, but the timing of their application remains critical. The judicious use of these insecticides would benefit from an effective forewarning system of likely wheat aphid infestation. For the effective management of many agricultural insect pests including aphids, long-term forecast models of pest pressure are essential (Kumari *et al.,* 2013). Crop modeling can act as a decision-making support system for concurrent climate scenarios. Several weather-based models have been developed for forewarning aphid infestation in a range of crop species; typically, these models rely on regression (either linear or non-linear) methods (Kumar *et al.,* 2012, 2016; Sharma *et al.,* 2015; Singh *et al.,* 2016). While the major purpose of forewarning is to trigger pest management measures in a timely fashion, it also facilitates communication between researchers and farmers. Web-enabled services, which typically utilize a three-tier architecture, consisting of presentation, application and data (Kumar *et al.,* 2008), are highly flexible and user-friendly. In order to address the need for such a system geared to the problem of wheat aphid infestation, the aim here was to develop a web-based forewarning system. The prediction models built in this study will help to predict the incidence and population surge of wheat foliar aphids in time, which in turn would aid in taking pre-emptive measures for successful pest suppression.

Materials and Methods

Data collection: The data used to develop and validate the weather-based regression model for forewarning of *R. maidis* and *R. padi* infestation were collected as the number of aphids/tiller weekly over twelve years (2006-07 to 2017-18) at Ludhiana (Punjab) and Niphad (Maharashtra), respectively. Ludhiana and Niphad are the hot spots for wheat aphids in India and thus selected for the development of prediction model. Weather data were available throughout the period 2006-07 to 2017-18, in the form of maximum and minimum air temperature, morning and evening relative humidity, and the number of hours of sunshine. These meteorological data for the respective locations were obtained from Punjab Agricultural University, Ludhiana (Punjab) and Agricultural Research Station, Niphad (Maharashtra). Crop age was counted from the date of sowing and the aphid population size was recorded at weekly intervals.

Development of models: The weather parameters were considered from the time of sowing of the crops till the time the forecasting was monitored. The use of data collected over short time intervals, however, necessarily increases the complexity of the model, so it is essential to identify a manageable number of parameters *i.e.,* at the same time as representative as possible of the variation in weather conditions. Here, weight was assigned to various parameters according to their importance in particular periods. Two indices were developed for each weather variable: one was an aggregate of the set of variables, and the other was a weighted total, based on correlation coefficients calculated between variables to forecast weather variables in each week. Similarly, to estimate the joint effect of weather variables, indices were calculated as weighted accumulations of the product of weather variables (taking two at a time), weights being correlation coefficients between variable to forecast and product of weather variables considered in respective weeks.

Among weather variables, numerical value 1 was assigned to the maximum temperature, 2 to minimum temperature, 3 to relative humidity (morning), 4 to relative humidity (evening), and 5 to the number of sunshine hours. The crop age at first appearance, peak appearance, and pest population were among the dependent variables whereas the meteorological variables were regarded as independent variables. At Ludhiana, weather data from the week of sowing, *i.e.* 45th Standard Meteorological Week (45 SMW) to 2nd SMW (of the subsequent calendar year) were utilized to assign the crop's age at the first appearance of aphids, while data up to 6 SMW (of the subsequent calendar year) were utilized to assign the crop's age at the time of peak population of aphids and the maximum number of aphids per tiller. Models for weekly monitoring of pest population size at Ludhiana were developed from data during the period 7-10 SMW. These data were considered to forecast the values 15 days before the actual occurrence of the pests in the field. Whereas at Niphad, weather data from the week of sowing, which was between 45 to 48 SMW were utilized to define the crop's age at the time of first appearance of aphids, while data up to 52 SMW was utilized to assign the crop's age at the time of peak population of aphids, and the maximum number of aphids per tiller. Models for weekly monitoring of pest population size at Niphad were developed from 1-4 SMW. A stepwise regression technique was used to develop the model. The partial F value for each variable in the regression was evaluated and checked for its significance, and any variable which featured a non-significant partial F value was removed from the model. The process was continued until no more variables were admitted, and none were rejected. Estimates of the root mean squared error, the mean squared error, and the mean absolute percentage error (MAPE) were taken as performance evaluation measures.

Web-enabled system: A web-enabled forewarning system based on statistical models was developed using three-tier architecture. The presentation tier was designed to make the system as user-friendly as possible. The system requires no prior set-up: the user merely needs to form a query based on what information is needed. The application tier provides the link between the user interface and the database. Its function is to convert the query into a form that can be recognized by the database. This task was achieved by mounting a set of scripts on the web server. These were arranged as active server pages (ASPs), which, to make the web pages as interactive and dynamic as possible; were written in HTML format. Java programming was used to generate the necessary codes. The connection to the database was achieved using an ASP so that when the user requests information, the application tier fetches the data from the database and provides the resulting information to the end-user in the form of a web page. The application tier was implemented in a Net Beans 8.0.2 Integrated Development Environment (https://netbeans.org/). The database (the data tier) houses a set of organized data, which can be used to access, modify, and update information. It runs on PostgreSQL9.3, which can function in any operating system (Linux, Unix, and Windows) environment. The forewarning system can be accessed from the link http:// www. wheat aphid forecast. iari. res. in /icar/cimmyt/ index. html. This system is highly interactive. Users' need to select crop, pest and then desired year and place to forecast the characteristics viz. crop age at the first appearance of pest, crop age at a peak population of pests and maximum population of the pest. Upon selection of these characteristics, a result on tentative population (aphids/tiller) along with crop age (days), will be displayed stating these characteristics of selected crop and pest for a particular year. Based on pest status, advisories for its control measure will be available to users. The population of pests may also be monitored on weekly basis, thus upon selection of year and place, the user can select the week to forecast the population, which is likely to occur in the selected week.

Results and Discussion

The models generated for the prediction of crop age both at the time of first appearance and the peak population of aphids and the maximum numbers of aphids per tiller at both locations are presented in Table 1, which also gives the relevant coefficients of determination (R^2). The equivalent models used for weekly monitoring of aphid numbers, with their R2 coefficients, are given in Table 2. Maximum and minimum temperatures, relative humidity in the morning and evening, and the number of hours with intense sunshine are the weather variables that were taken into account while developing the forecasting model. These factors were selected because they have the greatest impact on the aphid infestation of wheat crops. Any variations in these weather factors are directly related to variations in the infestation. Another assumption taken into account was considering these weather variables from the time of sowing of crops till the first appearance of pests, secondly till the peak population appeared in the field and finally the pest infestation monitoring. In these models, Z_{351} represents the weighted interaction of relative

Table 1: Predictive models for various aspects of aphids infestation on wheat at Ludhiana and Niphad with the coefficient of determination

Aphid spp. (Location)	Character to forecast	Model	R^2
Rhopalosiphum maidis (Ludhiana)	Crop age at first appearance of wheat aphid	Y_1=93.42537+0.00540*Z_{351}+0.1538*Z_{231}	0.92
	Crop age at peak population of wheat aphid	Y_2=118.40905+0.00524*Z_{351}+0.1571*Z_{231}	0.93
	Maximum aphid population	Y_3=-8.04479+0.01911*Z_{231}	0.87
Rhopalosiphum padi (Niphad)	Crop age at first appearance of wheat aphid	Y_1=17.33916+5.63940*Z_{51}+0.09166*Z_{451}	0.75
	Crop age at peak population of wheat aphid	Y_2=103.98022+0.01032*Z_{341}+6.19695*Z_{51}	0.74
	Maximum aphid population	Y_3=216.31773+0.69835*Z_{451}-0.66571*Z_{250}+ 61.16185*Z_{11}	0.98

Table 2: Models for weekly monitoring of aphids population on wheat at Ludhiana and Niphad along with their coefficient of determination

Pest (location)	Data used (SMW)	Models for Weekly Monitoring	R^2
Rhopalosiphum maidis	45 to 7th	$Y3=11.68181+0.01621*Z_{231}+0.02621*Z_{451}-0.12188*Z_{251}$	*0.98*
(Ludhiana)	45 to 8th	$Y3=25.23954+0.01455*Z_{231}+0.02765*Z_{451}-0.13464*Z_{251}$	0.97
	45 to 9th	$Y3=17.02994+0.01763*Z_{231}+0.02996*Z_{451}-0.29602*Z_{251}$	0.97
	45 to 10th	$Y3=15.57383+0.01762*Z_{231}+0.2514*Z_{451}-0.19300*Z_{251}$	0.99
Rhopalosiphum padi	45 to 1th	$Y3=1697.86793+0.25573*Z_{131}+97.73922*Z_{11}+0.98689*Z_{251}$	0.98
(Niphad)	45 to 2th	$Y3=2005.50382+0.88182*Z_{131}+62.91097*Z_{11}+1.24939*Z_{251}$	0.94
	45 to 3th	$Y3=2110.63672+0.15914*Z_{131}+34.53594*Z_{11}+1.60748*Z_{251}$	0.91
	45 to 4th	$Y3=2332.13947+0.17323*Z_{131}+16.71142*Z^{11}+1.40799*Z^{251}$	0.87

Table 3: Percent deviation between predicted and observed values of aphids infestation on wheat along with Mean Absolute Percentage Error (MAPE) at Ludhiana and Niphad

Year	Ludhiana			Niphad		
	Y1	Y2	Y3	Y1	Y2	Y3
2006-07	3.9	1.7	0.5	5.2	12.2	18.3
2007-08	1.4	1.7	2.5	14.3	2.2	17.6
2008-09	2.4	0.8	6.6	2.9	5.6	7.3
2009-10	1.3	1.9	0.8	0.7	2.3	46.5
2010-11	1.1	1.7	3.6	8.1	3.0	6.5
2011-12	1.3	1.6	0.7	8.0	1.8	52.0
2012-13	2.4	0.8	0.3	7.6	4.9	33.6
2013-14	1.3	0.0	1.0	15.7	1.1	1.3
MAPE	**1.9**	**1.3**	**2.0**	**7.8**	**4.1**	**22.9**

humidity in the morning with the number of hours of sunshine, Z_{231} the weighted interaction of minimum temperature and relative humidity in the morning, Z_{51} the weighted number of hours of sunshine, Z_{451} represents the weighted interaction of relative humidity in the evening with the number of hours of sunshine, Z_{341} the weighted interaction of relative humidity in the morning with relative humidity in the evening, Z_{11} the weighted maximum temperature, Z_{251} the weighted interaction of minimum temperature with the number of hours of sunshine, Z_{131} the weighted interaction of maximum temperature with the relative humidity in the morning. The R^2 estimates related to the crop's age at the time of first appearance of aphids ranged from 0.75-0.92 across the two locations. For the crop's age at the time of peak aphid population, the R^2 estimates ranged from 0.74-0.93, and 0.87-0.98 for the maximum number of aphids per tiller (Table 1).

Concerning the weekly monitoring of aphid numbers, the R^2 ranged from 0.87-0.99 across the two locations (Table 2). These high values of R^2 support the robustness of the models. Table 3 enumerates the deviations between the predicted and observed values, along with the MAPE statistics, and confirms the predictive power of the models. For each trait, the tests of randomness and the normality of residuals showed that, in most cases, the calculated values of the run test lay below 1.96, equivalent to a 5% threshold level of significance. Similarly, for each data set, the calculated values of the Shapiro-Wilk statistic lay within the acceptance region defined by a 5% level of significance. The conclusion was that none of the assumptions of randomness and normality of residuals was violated for any of the data sets. The various models were then validated over the four subsequent seasons at both locations. The levels of agreement between the predicted and observed values are illustrated in Fig. 1 (a-f), further confirming the validity of the models.

Statistical models are developed on crop age at the first appearance of pest, crop age at peak population of pest, maximum population of pest along with weekly monitoring of pest using weather variables. Considering these developed models in the background, a web based forewarning system was developed (www.wheataphidforecast.iari.res.in/icar/cimmyt/index.html). The screenshot of the home page of this system is presented in Fig. 2. Its front end was developed using HTML and CSS, the models were coded using Java and Java script. The output of the system, in the form of forewarning of aphid infestation concerning the predicted time of their first appearance of aphids, the time of their peak population, and the maximum number of aphids per tiller is given along with the advisories in the developed system. Based on the developed system, the aphid population in the wheat crop at two locations, Ludhiana (Punjab) and Niphad (Maharasthra) can be forecasted on weekly basis. In addition to these two locales, the developed forecasting model can also be extended for adjoining wheat growing regions sharing similar agro-climatic conditions. According to changes in weather

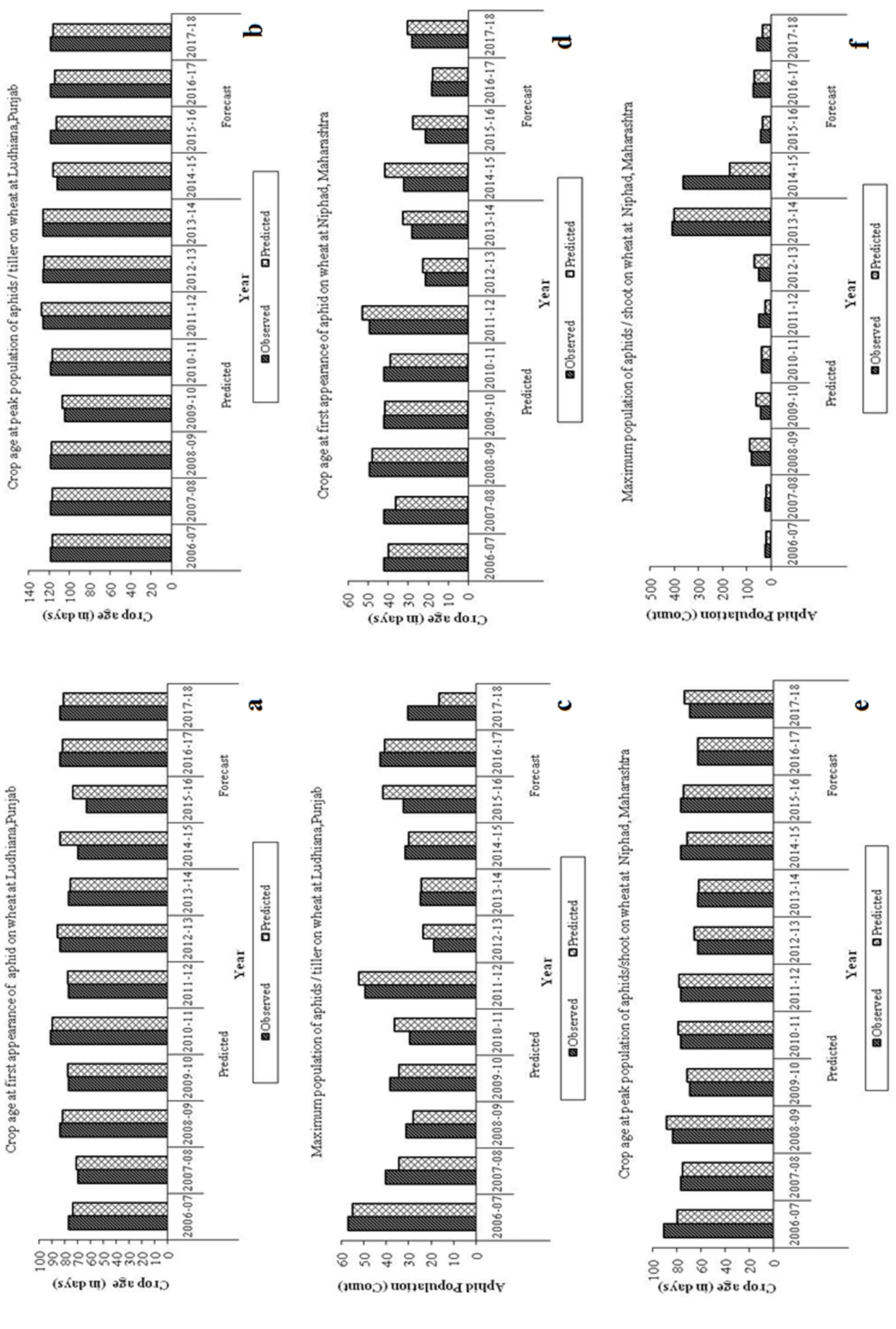

Fig. 1: Observed and predicted value for various parameters recorded related to aphids infestations on wheat at Ludhiana and Niphad.

Fig. 2: Home page of the web-enabled forewarning system for wheat aphids.

characteristics, these types of models have shown to be most effective in detecting pest and disease infestation (Agrawal and Mehta, 2007). The models may depict both low and high intensities of pest outbreaks (Chattopadhyay *et al.,* 2005). The prediction values obtained from the developed model were found to be pretty similar to the actual measured values in the field, as also reported by Kumar *et al.* (2016, 2018).

Since the normal sowing time of wheat in India is between the last week of October and mid-November (44-46 SMW), the model was designed using weather data from 45 SMW onwards. The historical data revealed that the highest aphid populations generally developed during 2-6 SMW at Niphad, while at Ludhiana, aphid populations peaked during 8-11 SMW. These results are in close proximity to the findings of Ahmad *et al.* (2016) and Dixit *et al.* (2019) who found that the aphid population commenced on wheat from the first or second week of January and reached a peak during the third week of March. Predictions were possible 1-2 weeks before the aphids' first appearance (51 SMW at Niphad and 2-3 SMW at Ludhiana); this extent of forewarning should be sufficient to provide the farmers enough time to procure and apply appropriate insecticides (Dean *et al.,* 2021).

Most models described in the literature have been based solely on weather conditions (Narayanasamy *et al.,* 2017). However, here weather data collected from the time of sowing until the time of the aphids' first appearance were integrated to develop informative weather indices. This approach may also take care of various biological phenomenons of the pests (like life cycle) as well as of the crops (Lessio and Alma, 2021). For predicting the crop's age at the first appearance of aphids at Ludhiana, the weighted interaction of relative humidity (RH) in the morning and the number of hours of sunshine (NHS) were found to be the key parameters, whereas at Niphad, the weighted NHS and the interaction between RH (evening) and NHS were important predictive parameters. Similar interactions were also computed for predicting the crop's age at which the population peaked at both locations. Chattopadhyay *et al.* (2005) also reported that models based on weather data and population dynamics of *Lipaphis erysimi* on rapeseed-mustard crop could provide effective prediction about the crop age as related to their time of first appearance and peak number on the crop. Likewise, for predicting the maximum aphid population at Ludhiana, the weighted interaction of minimum temperature and RH (morning) were important, while at Niphad, the key parameters were the weighted interaction of RH (evening) with the NHS. Thus, the weighted interactions of temperature, relative humidity and sunshine hours were found to be the most important parameters for wheat aphids' prediction.

The present results corroborated with Kumar *et al.* (2012) who developed web-based forecast software for prediction of aphids on oilseed Brassicas, using weather parameters as independent variables and crop age at time of first appearance of aphids on the crop, the peak number of aphid and crop age at peak population as dependent variables, fitted by multiple step-wise regressions. Elango *et al.* (2021) also used different prediction models by fitting covariates to the time series data and concluded that the autoregressive integrated moving average model with maximum temperature was best for predicting *Aleurodicus rugioperculatus* incidence. Similarly, Chiu *et al.*

(2019) also found temperature and humidity as key contributing exogenous factors in their prediction models to determine the abundance of *Trialeurodes vaporariorum* in greenhouses. Several forecasting systems, some based on accumulated air temperature (Coaker and Wright, 1963), others on soil temperature (Finch and Collier, 1986) and still others on a combination of weather parameters (Kumar *et al.,* 2012), have been suggested in the context of protecting crops from insect damage. In these systems, the farmers are required to input certain data to retrieve a forecast, but in reality, such information may not be available to them (Liu *et al*., 2022). With the system proposed here, in contrast, the user is only asked to provide the identity of the crop and the pest and his/her location, which is sufficient for the system to return the desired result. Because the system has been web-enabled, its forecasts are immediately disseminated to the user via internet.

The predictive power of any system depends heavily both on the validity of the underlying model and on the accuracy of the weather data used. The present model was successfully validated by testing against data obtained over four seasons at two locations. The precision of the weather data is considered to be high since it was collected by standard meteorological methods (Ghadekar, 2002). What has been described here is a prototype system developed to forecast the location-specific (Ludhiana and Niphad) infestation of wheat crops by aphids. The same approach can readily be adopted for other crops/ pest or disease combinations, provided that relevant historical data are available to formulate the models, as the one suggested for monitoring pest and disease threats in banana cropping system by Kreuze *et al*. (2022).

The system has been deliberately developed using open source software, and in such a way that there is no requirement for any additional software or hardware to be acquired before the forewarning system is implemented (Wang *et al*., 2022). It can be foreseen that the advice generated by the system can be widely disseminated through mobile phone networks, employing push notifications and also statistical models, which run in the backend of this forewarning system. It can be further enhanced in the future by incorporating the dynamic statistical model (in each year, the data will be added to this historical data, and the parameters of the model can be obtained) and the influence of biotic factors in the model (Singh, 2009).

The forewarning system though validated for two predominant wheat aphid species in India, *i.e., R. maidis* and *R. padi*, however it will work for the entire wheat foliar aphid complex. The model predicts the crop's age when aphids will either first appear, when their population will peak and what the size of the peak population will be. This information can be communicated to farmers well in advance to allow the effective timing of insecticidal sprays to protect the crop's productivity.

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Add-on Information

Authors' contribution: A. Kumar: Conceived the idea and designed the experiments, developed the statistical models and wrote the manuscript; **R. Sharma:** Developed the statistical models and wrote the manuscript; **B. Singh:** Performed the experiments; **S.D. Patil:** Performed the experiments; **C.P. Srivastava:** Conceived the idea and designed the experiments, developed the statistical models and wrote the manuscript; **G.P.Singh:** Performed the experiments; **A.K. Joshi:** Conceived the idea and designed the experiments, and wrote the manuscript.

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References

Agrawal, R. and S.C. Mehta: Weather based forecasting of crop yields, pests and diseases - IASRI Models. *J. Ind. Soc. Agric. Stat.,* **61**, 255-263 (2007).

Ahmad, H., I.M. Mir, D. Sharma, K. Srivastava, S.A. Ganai and S. Sharma: Seasonal incidence and management of wheat aphid, *Sitobion avenae*. *Indian J. Entomol.,* **78**, 148-152 (2016).

Babu, K.S., B. Singh, B.M. Mhaske and S.K. Sharma: Clothiandin, a new neonicotinoid insecticide for the management of foliar aphid complex of wheat in India and its safety to coccinellid predators. *Cer. Res. Comm.,* **40**, 296-303 (2012).

Chander, S., P.K. Aggarwal, N. Kalra and D.N. Swaruprani: Changes in pest profiles in rice-wheat cropping system in Indo-Gangetic plains. *Ann. Plant Protec. Sci.,* **11**, 258-263 (2003).

Chattopadhyay, C., R. Agrawal, A. Kumar, Y.P. Singh, S.K. Roy and S.A. Khan: Forecasting of *Lipaphis erysimi* on oilseed Brassicas in India – a case study. *Crop Prot.,* **24**, 1042-1053 (2005).

Chiu, L.Y., D.J.A. Rustia, C.Y. Lu and T.T. Lin: Modelling and forecasting of greenhouse whitefly incidence using time-series and ARIMAX analysis. *IFAC Papers Online,* **52**, 196-201 (2019).

Coaker, T.H. and D.W. Wright: The influence of temperature on the emergence of the cabbage root fly (*Erioischia brassicae*) from overwintering pupae. *Ann. Appl. Biol.,* **52**, 337-343 (1963).

Dean, A.N., J.B. Niemi, J.C. Tyndall, E.W. Hodgson and M.E. O'Neal: Developing a decision-making framework for insect pest management: a case study using *Aphis glycines* (Hemiptera: Aphididae). *Pest Manag. Sci.,* **77**, 886-894 (2021).

Deol, G.S., K.S. Gill and J.S. Brar: Aphid outbreak on wheat and barley in Punjab. *Newslett. Aphidol. Soc. India*, **6**, 7-9 (1987).

Dixit, A., P.K. Sharma, C.S. Jayaram and A. Rana: Population dynamics of wheat aphids and their natural enemies. *Indian J. Entomol.,* **81**, 916-920 (2019).

Elango, K., S.J. Nelson and P.D. Kumar: Incidence forecasting of new invasive pest of coconut rugose spiralling whitefly (*Aleurodicus rugioperculatus*) in India using ARIMAX analysis. *J. Agrometeorol.,* **23**, 194-199 (2021).

Finch, S. and R.H. Collier: Forecasting the times of attack of the cabbage root fly (*Delia radicum*) on vegetable brassica crops. *Ann. Appl. Biol.,* **12**, 37-46 (1986).

Ghadekar, S.R.: Practical Meteorology – Data Acquisition techniques, Instruments and Methods, Agromet Publishers, Nagpur, India, 68 pages (2002).

Ghosh, S. and R. Singh: Biosystematics of corn leaf aphid (Homoptera: Aphididae). *J. Aphidol.,* **16**, 109-124 (2002).

Khan, A.M., A.A. Khan, A. Muhammad and M.S. Iqbal: Wheat crop yield losses caused by the aphids infestation. *J. Biofer. Biopest.,* **3**,122 (2012).

Kreuze, J., J. Adewopo, M. Selvaraj, L. Mwanzia, P.L. Kumar, W.J. Cuellar, J.P. Legg, D.P. Hughes and G. Blomme: Innovative digital technologies to monitor and control pest and disease threats in root, tuber, and banana (RT&B) cropping systems: Progress and prospects. In: Root, Tuber and Banana Food System Innovations (Eds: G. Thiele, M. Friedmann, H.C.V. Polar and J.W. Bentley). Springer, Cham, pp. 261-288 (2022).

Kumar, A., P.W. Nemade, R. Sharma, R.K. Tanwar, C. Chattopadhyay, S.S. Wanjari and T.H. Rathod: Statistical forewarning models for sucking pests of cotton in Maharashtra. *J. Agrometeorol.,* **20**, 62-65 (2018).

Kumar, A., T. Misra, K. Batra, R. Sharma, A.K. Mishra, S. Vennila, R.K. Tanwar, N. Singh, P. Wahi, R. Rajendran, D.K. Sidde Gowda, P.S. Sarao, V.N. Jalgaonkar, S.K. Roy and C. Chattopadhyay: Web enabled and weather based forewarning of yellow stem borer [*Scirpophaga incertulas* (Walker)] and leaf folder [*Cnaphalocrcis medinalis* (Guenee)] for different rice growing locations of India. *Mausam*, **67**, 861-868 (2016).

Kumar, K.M.: A checklist of species of the genus *Rhopalosiphum* from Bihar. *Indian J. Entomol.,* **76**, 350-352 (2014).

Kumar, V., A. Kumar and C. Chattopadhyay: Design and implementation of web-based aphid (*Lipaphis erysimi*) forecast system for oilseed Brassicas. *Ind. J. Agric. Sci.,* **82**, 608-614 (2012).

Kumar, V., S. Lehri, A.K. Sharma and A. Kumar: Design and implementation of agricultural research digital photomanager. *Compu. Electro. Agric.,* **60**, 296-300 (2008).

Kumari, P., G.C. Mishra and C.P. Srivastava: Forecasting of productivity and pod damage by *Helicoverpa armigera* using artificial neural network model in pigeonpea (*Cajanus cajan*). *Int. J. Environ. Agric. Biotech.,* **6**, 335-340 (2013).

Lessio, F. and A. Alma: Models applied to grapevine pests: A review. *Insects*, **12**, 169 (2021).

Liu, C., Z. Zhai, R. Zhang, J. Bai and M. Zhang: Field pest monitoring and forecasting system for pest control. *Front. Plant Sci.*, **13**, e990965 (2022).

Narayasamy, M., J.S. Kennedy and V. Geethalaksmi: Weather based pest forewarning model for major insect pests of rice – an effective way for insect pest prediction. *Ann. Res. Rev. Biol.,* **21**, 1-13 (2017).

Navarro, E.C., S.K. Lam and P. Trebicki: Elevated carbon dioxide and nitrogen impact wheat and its aphid pest. *Front. Plant Sci.,* **11**, e605337 (2020).

Patil, S.D., K.M. Sonawane and V.S. Pawar: Efficacy of various insecticides against foliage feeding wheat aphids. *Int. J. Plant Protec.,* **7**, 111-114 (2014).

Puri, S.N.: India (1). In: Farmer-led Integrated Pest Management in India and the Pacific, Asian Productivity Organization, Tokyo, Japan, pp. 83-108 (2000).

Sharma, P., P.D. Meena, A. Kumar, V. Kumar and D. Singh: Forewarning models for Sclerotinia rot (*Sclerotinia sclerotiorum*) in Indian mustard (*Brassica juncea* L.). *Phytoparasitica*, **43**, 509-516 (2015).

Shekhar, S.M.V. and V.S. Singh: Spatial distribution pattern of aphids infesting wheat. *Indian J. Entomol.,* **61**, 396-400 (1999).

Shrivastava, S.K., R.K. Verma and B. Singh: Integrated pest management in wheat. In: Wheat: Recent Trends on Production of Wheat in India (Eds.: R.S. Shukla, P.C. Mishra, R. Chatrath, R.K. Gupta, S.S. Tomar and I. Sharma). Jawaharlal Nehru Krishi Vishwa Vidyalaya, Jabalpur and ICAR-Indian Institute of Wheat and Barley Research, ICAR, Karnal, Haryana, India, pp. 197-209 (2014).

Singh, B. and G.S. Deol: Quantitative grain yield losses caused by aphid complex in wheat. *Crop Res.,* **26**, 501-504 (2003).

Singh, B., S. Kaur and P. Chhuneja: Evaluation of plant resistance in progenitors of wheat against foliage feeding aphids. *Agric. Res. J.,* **55**, 117-121 (2018).

Singh, B.: Incidence and comparative development of wheat aphids and effectiveness of coccinellid beetle on wheat and barley in Punjab. *J. Insect Sci.,* **21**, 380-384 (2009).

Singh, S.K., A. Kumar, R. Agrawal, H. Kumar, C.P. Srivastava, D.C. Singh, A. Katiyar, S. Singh and J. Kumar: Predicting pod fly (*Melanagromyza obtusa* Malloch) incidence on long duration pigeonpea in Uttar Pradesh. *J. Food Legumes*, **29**, 51-56 (2016).

Wang, R., R. Li, T. Chen, J. Zhang, C. Xie, K. Qiu, P. Chen, J. Du, H. Chen, F.R. Shao, H. Hu and H. Liu: An automatic system for pest recognition and forecasting. *Pest Manag. Sci.,* **78**, 711-721 (2022).