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Forecasting of exotic bondars nesting whitefly, *Paraleyrodes bondari* Peracchi (Hemiptera: Aleyrodidae) by prediction models

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Abstract

Whiteflies, as polyphagous pests, hold global significance due to their substantial economic impact. In recent times, the exotic bondar's nesting whitefly (BNW), *Paraleyrodes bondari* Peracchi (Hemiptera: Aleyrodidae) Martin, has profoundly disrupted the horticultural ecosystem in India. This disruption has garnered significant attention of agricultural communities. The severity of its influence has been exacerbated by shifting of weather patterns and climatic conditions. To address these challenges, a comprehensive study was initiated in a coconut plantation. The primary objectives of this study were to unravel the factors that exert influence on the behavior of the bondar's nesting whitefly and furthermore, to develop predictive models aimed at forecasting its incidence. The correlation studies conducted between biotic and abiotic factors and the population of BNW revealed noteworthy findings. Notably, maximum temperature (with a correlation coefficient i.e. r = 0.28*), bright sunshine hours (r = 0.3*), and canopy temperature (r = 0.28*) exhibited a significant positive influence on the whitefly population build up. These results underscore the crucial role that climatic conditions play in driving the dynamics of BNW population. The prediction of BNW outbreaks based on prevailing weather conditions and the timely implementation of appropriate control measures for effective pest management are of paramount importance. Among the prediction models assessed, artificial neural network (ANN) models emerged as the most promising. The model demonstrated superior performance and were identified as the optimal choice for accurately predicting BNW incidence.

Keywords: Weather. Bondar's nesting whitefly. Prediction models. Artificial neural network

Introduction

Globalization has exerted a profound influence on international agricultural trade, facilitating the movement of goods and planting materials across borders. This interrelation carries inherent risks, notably the potential introduction of invasive pests. Despite the implementation of stringent quarantine measures, numerous insect pests have managed to breach these defenses. The consequences of such invasions are far-reaching, exacting a considerable toll on biodiversity and exerting a substantial adverse impact on agricultural crop production and a nation's economy. India has experienced the infiltration of diverse species of exotic whiteflies, in particular, during the period from 2016 to 2021 that has raised significant biosecurity concerns (Sadhna et al. 2023). Infestation of Bondar's nesting whitefly (BNW), *Paraleyrodes bondari* Peracchi (Hemiptera: Aleyrodidae) on Citrus species was first described from Brazil in 1971 (Peracchi 1971) and later in 2011, it was detected in Florida USA (Stocks 2012) where it is considered as an emerging pest. Remarkably, the scope of its invasion in new geographic area and exploitation of host plants have expanded rapidly since its initial introduction. In India, its occurrence was first reported from coconut palms in Kerala (Josephrajkumar et al. 2019). Then, the invasion expanded across the states including the Eastern region of the country (Sankarganesh and Roy 2021). BNW exhibits a polyphagous nature, coexisting with various other whitefly species and sustains itself by extracting nutrients through desapping solute from the upper leaf surfaces (adaxial) of a diverse range of plants, particularly on coconut. This feeding behavior inevitably contributes to the weakening of the host plants.

The weather conditions play a pivotal role in triggering the resurgence of this pest, providing a favorable environment for its rapid proliferation and widespread dissemination (Srinivasan et al. 2016). The BNW is highly responsive to fluctuations in weather patterns, particularly those that create conducive circumstances for its growth and development. The variation in the nature and extent of damage is also influenced by the age and health of the plantation, overall health of the ecosystem and presence of natural enemies that can regulate the whitefly population. However, the climatic conditions exert a significant influence on the survival, development, outbreaks, reproductive capacity and activity of pests (Fakhri and Jamal 2012). Also, abiotic factors significantly influence the occurrence and prevalence of this pest and

its natural enemies within a crop ecosystem. The natural enemies play a pivotal role in suppressing the whitefly population in its natural habitat (Kumar et al. 2018; Sankarganesh et al. 2023). Thus, accounting for natural enemies becomes indispensable. Nevertheless, the primary challenge in addressing the pest management issue lies in the sufficient understanding of the pest dynamics. Comprehending these aspects assume critical importance in anticipating potential outbreaks and identifying susceptible phases within the pest's life cycle. This knowledge enables the identification of stages where control measures can wield the most impactful results. The whitefly incidence varies with the season, the knowledge of the relationship between insect pests and climatic factors is crucial for developing region-specific strategies for its management. Through a meticulous examination of various variables, including climatic conditions and plant health, the study sought to provide valuable insights. The population buildup of any insect is very intimately related with the prevalent weather parameters (Boopathi et al. 2017). Utilization of a forecast model to determine the habitat suitability for the growth and development of invasive species under changing climatic conditions has the potential to enhance management strategies and curtail their expansion into new geographical regions (Kumar et al. 2015). Also, forecasting enables to prevent outbreaks and epidemics of pest incidence. The current work analyzed the pest dynamics in the context of coconut plantation along with prediction models. The developed prediction model would be helpful for devising proactive and precisely targeted strategies for pest management.

Materials and methods

Seasonal incidence and dynamics of bondars nesting whitefly

A study was conducted from 2021 to 2022 in a four-year-old coconut plantation situated at geo-coordinates 22.9876° N latitude and 88.4552° E longitude (Nadia, West Bengal, India). The selected plantation was devoid of any pesticide exposure. A total of ten coconut palms were randomly selected from the plantation to facilitate the recording of observations concerning the seasonal prevalence of BNW. Within each palm, a trio of fronds especially one each from the upper, middle, and lower portions were selected. In each frond, ten leaflets were tagged for taking count on the population of BNW. The commencement of the study was coincided with 40^{th} standard meteorological week of 2021. On a weekly basis, thorough observations were undertaken from the chosen leaflets of the coconut trees. The population of *P. bondari* was quantified using a magnifier with a 15x magnification. The recorded populations of BNW were

correlated with pertinent weather variables in accordance with the methodology outlined by Panse and Sukhatme (1954). To know the association of natural enemies with *P. bondari*, the population counts of predators were recorded at weekly intervals from the tagged leaflets. The population of natural enemies was also correlated with the relevant weather variables.

Weather parameters

The multiple correlation analysis between the population of BNW (as dependent variable) and natural enemies and prevailing weather variables together (as independent variable) was worked out in 'R' statistical package (Harrell 2022). The weather data *viz.,* maximum temperature (°C), minimum temperature (°C), morning relative humidity (%), evening relative humidity (%), total rainfall (mm), wind speed (km/hr) and sunshine (hrs) were procured from the ICAR-AICRP on Agro-meteorology, BCKV, Nadia, West Bengal, India for the entire study period. Further, the canopy temperature (°C) of the coconut palm was meticulously measured with the help of Raytek infrared thermometer (Mini Temp MT 4).

Time series modelling

Time series modeling was carried out between the data collected on insect occurrence and corresponding climatological variables within the same time interval. The study focused on fitting both linear and non-linear models to predict the population density of the BNW population using various biotic and abiotic factors. To explore the relationships between BNW population and these factors, a scatter plot matrix, predictive modeling techniques, namely the dynamic linear time series Autoregressive Integrated Moving Average with Exogenous variables (ARIMAX) and non-linear Artificial Neural Network (ANN) models were utilized to forecast the BNW population density. The entire dataset was split into training and testing subsets, allocating 85% of the data for model fitting and the remaining 15% for model validation. All statistical analyses were performed using 'R' software version 4.2.1 (Harrell 2022).

Autoregressive integrated moving average with exogenous variables (ARIMAX)

The short-term forecasting of variables with past values states the ARIMA model, the generalization of this model along with covariates (x) which have an impact over the predictors (y) (Bierens 1987). Where, k numbers of x_t are exogenous independent random variables *viz.,* biotic and abiotic factors and y_t over time series process (y_t, x_t) with (k+1) terms is given by

$$\nabla^d y_t = \sum_{i=1}^{p} \phi_i \nabla^d y_{t-i} - \varepsilon_t - \sum_{j=1}^{q} \theta_j \nabla^d \varepsilon_{t-j} + \sum_{k=1}^{r} \nabla^d \beta_k x_{kt}$$

where, ∇^d difference series, p - number of lags of BNW population density (y) or autoregressive order AR(p), q - number of lags of random term or moving average MA(q), r - number of biotic and abiotic factors (x) and ε_t - error at time *t* follows a normal distribution (0, σ^2) (Sarkar et al. 2023).

Initially, the constancy of mean and variance over time for the weekly BNW population density data was assessed using the Augmented Dickey-Fuller (ADF) test. Besides, the order of autoregressive and moving averages was determined through the examination of partial autocorrelation function (PACF) and autocorrelation function (ACF) plots of the differenced or stationary series. To mitigate insignificant 't' ratios within the model the first-difference form of the exogenous variables was adopted (Gujarati 2004). Subsequently, the ARIMAX model was fitted across various combinations of lags and exogenous independent variables. The selection of the optimal model was based on the criteria of minimizing the Akaike information criterion (AIC) and the Schwartz-Bayesian criterion (BIC) (Kumari et al. 2019). The per cent of total variability explained by the model is given by R^2 value.

$$AIC = -2L+2(p+q+1+r),\ BIC = -2L+ 2(p+q+1+r)\ log(n)$$

Where, n- number of observation in BNW population and L-loglikelihood

Artificial neural networks (ANN)

An artificial neural network was employed to forecast the intricate and non-linear characteristics of data featuring numerous covariates (Aguilar et al. 2020). These networks undergo training interactions until the sum of squared errors reaches a minimum. To establish the model, the BNW population data, along with the biotic and abiotic datasets, were divided into training and testing subsets. The data was then subjected to transformation using min-max scaling techniques. The architecture of the model was crafted through a process of trial and error, allowing for the determination of its optimal topology (Beres *et al.,* 2017).

The ANN model output is given by

$$\hat{Y} = f\left\{\sum_j^n W_{kj}\, f\left(\sum_i^m W_{ij} X_i + b_j\right) + b_k\right\}$$

where, f is an activation function, b is biased and x_k is the biotic and abiotic factors, W- weights between nodes, n is the number of neurons in the input layer, m is the number of neurons in the middle layer, and i, j, k are neurons of the input, middle and output, respectively.

Forecast evaluation methods.

For comparing the forecasting performance of distinct models, error range indices such as root mean square error (RMSE), root median square error (RMdSE) and mean square percentage error (MAPE) were utilized. The RMSE quantifies the disparity between the actual BNW population series (y) and its predicted level by the model ($\hat{y}$), while the RMdSE evaluates the model's resilience to outliers by computing the square root of the median of squared deviations which is given as

$$\text{RMdSE} = \sqrt{median(y - \hat{y})^2}$$

Results and discussion

Correlation studies of bondars nesting whitefly

The weekly observations were recorded on the populations of BNW, *P. bondari*, and its natural predators. The BNW population exhibited a year-round presence and infestation on coconut palms. Seasonal fluctuations revealed that *P. bondari* infestation was minimal during the wet season and peaked during the summer months. The elevated temperatures during summer accelerated metabolic activities, leading to a rapid increase in pest population. The results from the multiple correlation analysis as depicted in (Fig. 1), elucidated the relationship between *P. bondari* population and various biotic and abiotic factors. The correlation analysis unveiled that maximum temperature (r = 0.28*), bright sunshine hours (r = 0.3*), and canopy temperature (r = 0.28*) exhibited a significant positive influence on the BNW population. Wind speed (r = 0.12) and minimum temperature (r = 0.01) displayed positive correlations with the BNW population on coconut trees. Conversely, a notably negative correlation was observed between *P. bondari* and evening relative humidity (r = -0.5**) as well as rainfall (r = -0.37**). These findings are in accordance with prior research on invasive whiteflies (Mani and Krishnamoorthy 2000; Elango and Nelson 2021; Chavan et al. 2022). The correlation analysis involving weather variables holds particular significance, as climatic conditions play a pivotal role in shaping the dynamics of the BNW population. Sarma et al. (2021) reported that rainfall had minimal impact on the short-distance dispersal of the pest. However, heavy rainfall and prolonged wet spells, coupled with continuous rainy days, influenced the dispersal of the rugose spiraling whitefly. Besides, the impact of natural predator populations on *P. bondari* was observed to be negative and statistically

significant (r = -0.3*) in relation to coccinellids. Similar observations on the natural enemies of whiteflies were made by (Geetha 2000).

ARIMAX model fitting

Based on the results of the ADF test, the actual weekly time series data of the BNW population demonstrates non-stationarity. Consequently, in such instances, it may not be possible to reject the null hypothesis at a 1% level of significance in favor of stationarity. To address this, the series was altered iteratively until achieving stationarity, which was attained at the second difference, as indicated in the Table 1.

The ACF and PACF plots of the second differenced series (Fig. 2) clearly exhibit significance at the first lag.

The ARIMAX model was applied across various combinations of p, q and the biotic and abiotic factors linked to the BNW population. Among these, the ARIMAX (1,2,1) model, incorporating exogenous variables such as COC (Coccinellids), CRY (Chrysopids), maximum temperature, minimum temperature, morning relative humidity, evening relative humidity, rainfall, bright sunshine hours and canopy temperature were chosen to construct the optimal model. The selection was based on the model's lowest AIC and BIC values, smallest variance (σ^2) and the highest R^2 value (86 %). Similarly, Elango et al. (2021) investigated various prediction models by incorporating covariates into the time series data. It was determined that ARIMA (0,2,1) with maximum temperature emerged as the optimal weather variable for developing forecasting model of rugose spiraling whitefly incidence. Among all the covariates, only maximum temperature was identified as a significant predictor, while the remaining covariates were found to lack significance. Further details, including coefficients and standard errors are provided in Table 2.

ANN model fitting

Although the Pearson correlation coefficient has exhibited the degree of linear association between the dynamics of the BNW population and biotic as well as abiotic factors, it is noteworthy that some variables such as COC (Coccinellids), CRY (Chrysopids), morning relative humidity, evening relative humidity and bright sunshine hours exhibited non-linear relationships. These observations are evident from the scatter plot matrix (Fig. 3). Consequently, an artificial neural network (ANN) model was developed using the same exogenous variables as those utilized in the best-fitting ARIMAX model. Additionally, variations of the ANN model were constructed, both with and without the inclusion of the first lag of BNW population data.

For the first hidden layer of the ANN model, the number of neurons was randomly selected within the range of 4-6. Various ANN topologies were thus created, incorporating logistic and hyperbolic tangent non-linear activation functions. After evaluating different configurations, the ANN model featuring a logistic activation function, a lag value of the BNW population, and 4 neurons in the first hidden layer demonstrated superior performance. This determination was based on the model's ability to achieve the lowest RMSE and MAPE values in both the training and testing datasets. The architecture of the selected model is depicted in Fig. 4.

Residual diagnostics

To assess the adequacy of the fitted ARIMAX model, both the Shapiro-Wilk and Box-Ljung tests were conducted. The Shapiro-Wilk test was utilized to evaluate normality, while the Box-Ljung test assessed the presence of autocorrelation within the residuals. A probability value below 5% was indicative of non-normality and autocorrelation. For the ARIMAX model, the residual distribution was found to be non-normal, yet serial correlation was absent. In contrast, the ANN model, being non-parametric, undergoes residual diagnostics as well, satisfying the conditions outlined in Table 3. To sum up, the optimal model for forecasting future BNW population was determined using RMSE and RMdSE measures, which are detailed out in Table 4. The ANN model was considered to be the best model to predict the BNW population. The fitted and actual BNW population through the ANN model is presented in Fig. 5.

Chattopadhyay (2021) underscored the growing significance of addressing weather and climate risks in agriculture due to climate change. The mapping and prediction of invasive pest occurrences in potential areas are crucial in the current scenario. Bentlage et al. (2013)

emphasized integrating ecological niche models with species distribution as the most suitable approach for predicting the potential distribution and spread of various pests. The prevalence and distribution of the spiraling whitefly by employing maximum entropy (MaxEnt) model was studied and habitat suitability for pest incidence was forecasted (Selvaraj et al. 2022). Nonetheless, the suitability of each model varies in accordance with changes in pest dynamics. In the present study, the ANN model emerges as the superior choice for BNW population prediction, boasting lower values of RMSE and RMdSE when contrasted with the ARIMAX model.

Conclusions

Based on the findings, it is evident that the temperature emerged as the prevailing factor influencing the population flare-up of BNW. By implementing customized control measures considering distinct agro-climatic conditions and specific local factors, it becomes possible to mitigate the detrimental impact inflicted by this exotic pest upon coconut plantations in India. The study explored the effect of various weather parameters on BNW and its natural enemies. The suggested model may serve as a valuable tool for evaluating the occurrence and rapid escalation of nesting whitefly populations. Understanding the influence of climatic conditions on the dynamics of both the pest and its predators an effective crop protection strategy can be devised. The results offer valuable insights both for scientific and agricultural communities, presenting a pathway towards proactive and efficient management of bondar's nesting whitefly infestations. By leveraging the predictive models, stakeholders can enhance their ability to anticipate and address BNW outbreaks, thereby minimizing the economic and ecological impacts associated with this pest.

Authors contribution

Conceptualization of the idea of research and designing of the experiment by E.S. & K.R.; execution and data collection by E.S.; analysis of data by N.E. & T.G.; interpretation of data by E.S.& N.E. and preparation of the manuscript by E.S.& K.R.

Declarations

Conflict of interest: All authors declare that they have no potential conflict of interests.

Research involving human participants and/or animals: Not applicable.

Informed consent: All authors have reviewed the manuscript and approved its submission for publication.

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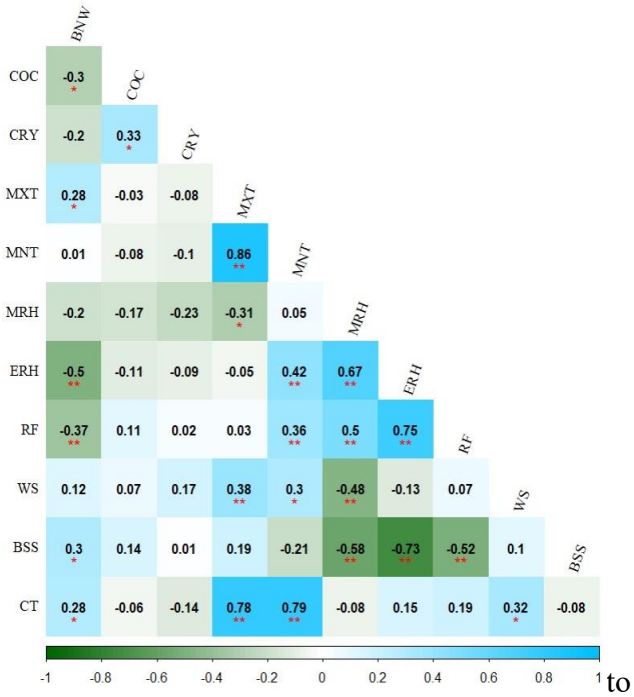
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to

BNW: Bondars nesting whitefly, COC: Coccinellids, CRY: Chrysopids, MXT: Maximum temperature (˚C), MNT: Minimum temperature (˚C), MRH: Morning relative humidity, ERH: Evening relative humidity (%), RF: Rainfall (mm), WS: Wind Speed (km/hr), BSS: Bright Sunshine (hrs), CT: Canopy temperature (˚C)

Fig. 1 Pearson's correlation coefficient (r) between *P. bondari* population and both biotic and abiotic factors

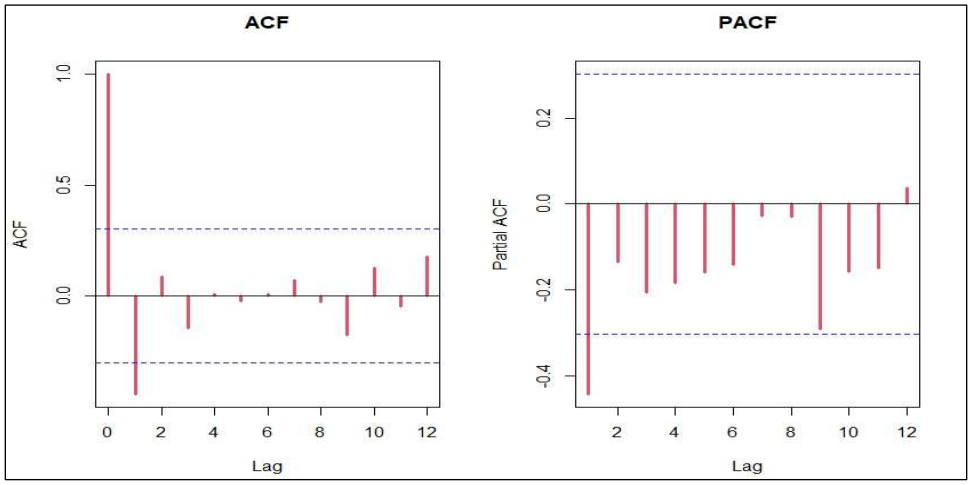


Fig. 2 Autocorrelation and Partial autocorrelation function at the second difference of BNW population incidence

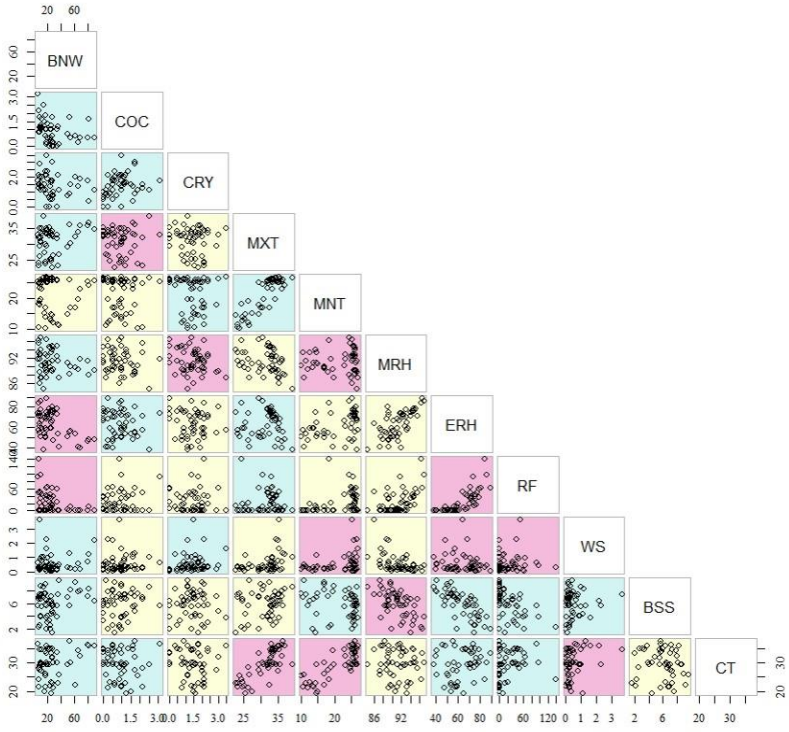


Fig. 3 Scatter plot matrix among BNW population, biotic and abiotic factors

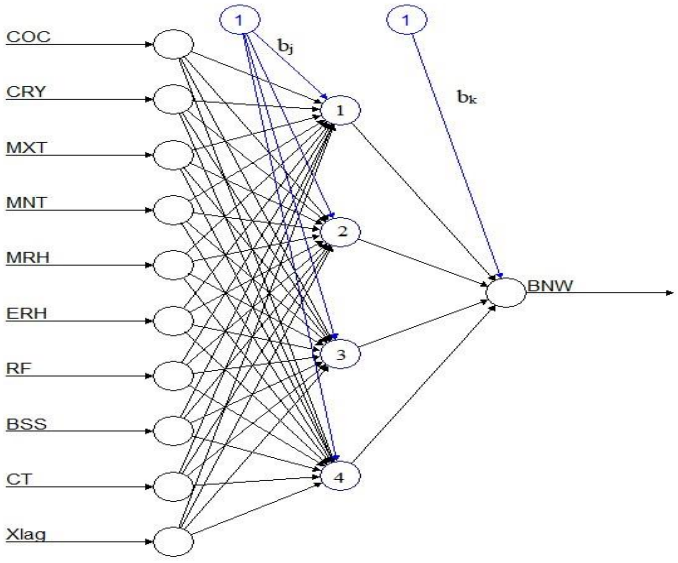


Fig. 4 Topology of best-fitted ANN model

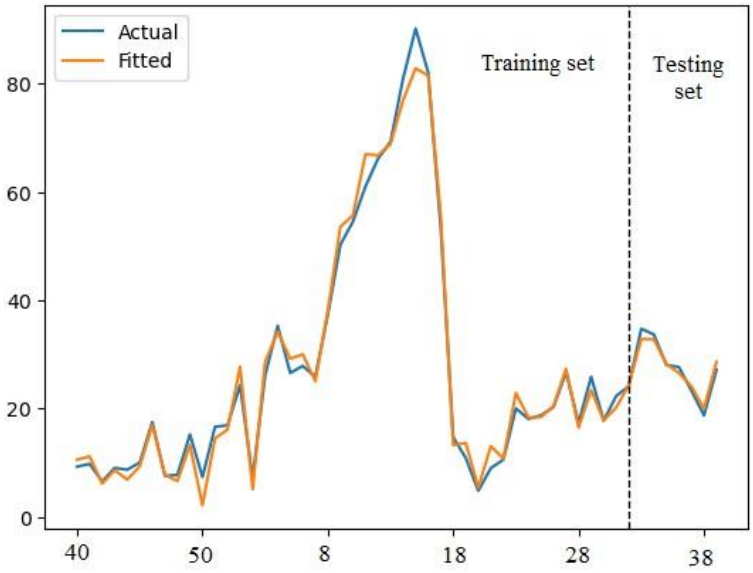


Fig. 5 Actual vs fitted values of BNW population incidence through ANN model