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Forecast results of some major insects damaging the tobacco plants in Vietnam based on weather conditions

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Abstract

Tobacco budworms and aphids are the major pests in tobacco-growing areas of Vietnam. Aphids do not only cause direct damage but also transmit many viruses, such as potato virus Y, Cucumber mosaic virus, etc. To effectively prevent pests and diseases, contributing to reduce damage caused by insect pests and the use of pesticides, in recent years, the tobacco institute has built a combined predictive model between Skybit models, Fuzzy and Degree days that is run on the Excel software. Based on the interaction between the pest, environmental conditions (temperature, humidity, rainfall), and the development stage of tobacco gives forecast results and advises the best controls. Through the study results show that the accuracy of forecast the tobacco budworms and aphids is from 83% to nearly 100%. For the aphids, the model that combines between the Skybit and Fuzzy has the most accurate predictive effect. Forecast the aphids by the Degree Days model is low predictive efficiency and can not apply in forecast the tobacco aphids. With tobacco budworms, forecast model that combines between Skybit models, Fuzzy and Degree days gives the highest predictive results. The predictive model is more accurate when the the weather factors little change. Based on the predictive and observable results, we give the best control methods that reduce the damage caused of insect pests; reduce the use of pesticides compared to years ago; increase yield and quality; and increase income for tobacco-growing farmers.

Keywords: The tobacco Aphids, Budworms, Forecast model, and Tobacco

1. Introduction

Tobacco is an important economic crop in many countries around the world. Major tobacco-producing countries around the world include China, India, Brazil, and the United States. Tobacco is a high-value crop, earning more cash per hectare than most other crops, such as corn in the United States (Johnson P.R, 1984). Like many economic crops, tobacco is subjected to damage by several species of insects from the greenhouse and the field stage. The insects that attack the growing crop include hornworms, tobacco budworms, flea beetles, aphids, splitworms, green June beetle larvae, and Japanese beetles. Some major harmful species are tobacco aphids, black cutworms, budworms, hornworms, thrips, Japanese beetles, and tobacco wireworms. However, the occurrence and damage of these insects vary from region to region (PA. Edde, 2018).

Currently, many countries in the world have used weather data to forecast pests and diseases of many crops. Some current popular forecasting models are the Skybit, Degree Days (DD), and the Fuzzy logic model. Forecast results that based on weather data have an accuracy of up to 85% for pests (Ching-Ju Chen et al., 2012), 75 - 95% for insects on rice in India (Vennila S et al., 2016), from 81.6 - 89.9% for fungi (Fatthy Amir, 2016). Skybit model is developed by Joe Russo in 1993 and used weather data to predict the plant diseases and insects for many crops in the world, such as apples, carrots, grapes, peanuts, potatoes, tomatoes, and wheat (Matthew Wallhead et al., 2017). Predicting by degree days: Insects are cold-blooded animals, and the temperature plays an important role for their growth and development. Each insect has a temperature threshold for its growth and development, such as Base development temperature (Tbase), Upper development temperature (TU), and optimum temperature level (TLopt). Development of insects can not occur when temperatures are below Tbase or above TU (termed upper cutoff). Insects have an optimum temperature range in which they quickly grow and cause severe harm (Ric Bessin and Raul Villanueva, 2019). The fuzzy logic model has used in many applications in agriculture. It is applied to forecast insects and diseases based on weather factors, such as temperature, relative humidity, leaf wetness, etc. The activity of organisms only happens when proper temperature and humidity levels (Vidita Tilva et al.,2013). The fuzzy will evaluate the relationship between leaf wetness, temperature and days after fungi inoculation (Fatthy Amir, 2016).

Insects develop rapidly in warm weather, and their population can build up quickly in favourable weather conditions and destructive natural enemies. The meteorological parameters affect pest abundance and distribution. Temperature is the most crucial factor influencing the rate of growth and development of insects. Relative humidity (RH) is the chief weather parameter directing the activity of insects and diseases. The interaction between pest activity and abiotic factors helps to predict and give control methods (Khan MMH, 2019). Heavy rain in a lot of day results in the death of *H. armigera* (Ge F et al., 2003). The high increasing air humidity and soil water content increase the deadly rate of pupae (Chen FJ et al., 2003) and decrease the capable flight action, copulation, and fecundity of butterflies. The flight action of adults depends on relative humidity. The flight action is the best when RH ranges from 60 to 90% (Wu KM and Guo YY, 1996; Li Z et al., 2016). Temperature is related to the flight action of *H. armigera* (Wardhaugh KG et al., 1980), most favourable temperature levels range from 20 to 22°C (Gao YB et al., 2010), 20 to 24°C (Wu KM and Guo YY, 1996) lead to increase the flight distance and population spreading of moths lead to the insects strongly develop in the

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field. To study the results of Nguyen Van Chin, 2021, feeding tobacco budworms in the laboratory with a temperature of 20.5^{o}C and humidity of 63%, the mortality rate of larvae reached 96.15%, and the pupae did not mature. At a temperature of 29.6^{o}C and humidity of 80.6%, the mortality rate of the one instar larvae was up to 82.76%.

In Vietnam, tobacco transplants in many provinces, including Cao Bang, Bac Kan, Lang Sơn, Gia Lai, and Tay Ninh, with an annual area of over 5.500 ha, and damage by many species of insects and diseases, such as tobacco aphids, black cutworms, tobacco budworms, tobacco caterpillar, powdery mildew, frog eye, black shank, target spot, brown spot, etc. The main species in the growing tobacco are tobacco budworms, aphids, powdery mildew, frog eye, target spot, etc. Every year these insect pests arise and affect growth, yield and quality. According to plant protection experts, every year in Vietnam, the yield loss due to pests and diseases is estimated at 10 - 30%. To limit yield and quality losses caused by insect pests, forecasts and advice on tobacco pest control are very important for tobacco-growing regions in Vietnam. To forecast insects and diseases in tobacco, Vietnam Tobacco Institute has applied the forecast model based on the weather and climate to build a forecast model based on the Skybit, Fuzzy, and Degree-days models (Nguyen Van Chin et al., 2022 and Nguyen Van Chin, 2021). The model has been studied for many years and continues to be improved from 2021 to 2022.

To forecast and advise on effective insect and disease control to minimize the damage caused by pests in tobacco-growing areas of Vietnam, the Tobacco Institute has built a pest forecasting model based on skybit, degree days, and Fuzy and runs on Excel software. Forecast results help us give the best control methods to prevent the growth and harm of organisms, reduce the use of pesticides, and increase the farmer's income. The model continues to be studied and improved next time to increase predictive and control effects.

2. Materials and Methods

Forecast Areas: The tobacco-growing regions of Vietnam as Cao Bang and Tay Ninh. Cao Bang is a province in Northern in Vietnam, with four seasons a year. But the most obvious are summer and winter, with temperature variations, little rainfall and uneven distribution. The average annual rainfall is about 1.500 mm, and the number of rainy days in a year is 128 days. The rainy season is from April to September, accounting for 70% of the annual rainfall and concentrating on June, July and August. The average temperature is 20^{o}C - 24^{o}C, and the average humidity is 80% - 90%. The dry season is from October of the previous year to March of the following year. The dry season is cool, foggy, and dry. The cold months are from December to February. The average rainfall, temperature, and humidity are 20 - 40mm, 8 - 15^{o}C, and 70% - 80%, respectively. Tay Ninh region has rainy and dry seasons. The dry season is from December of the previous year to April of the following year, with little rain and low humidity. The rainy season is from May to November, with lots of rain and high humidity. The annual average temperature, rainfall, and humidity are 27 - 28°C, 1.800 - 2.200 mm, and 70 - 80%, respectively.

Forecast Objects: Some main organisms cause the tobacco, such as Budworm (*Helicoverpa assulta*) and (*Myzus persicea*) in Vietnam.

Forecast time and the growing stage of tobacco: Cao Bang region: From 01st January to 30th April, 2023 and Tây Ninh region: 15th Decembe, 2022 to 15th April, 2023, corresponding to the transplanting to harvesting time.

Weather Data for the Forecast: Weather forecast data of the fifteen days in Cao Bang and Tay Ninh are synthesized from weather websites, such as Myweather2.com, Tutiempo.net, Myforecast.com, and Vietnam national centre for Hydro-meteorological forecasting.

Forecast method: Our predictive model is built based on the Skybit, Fuzzy, and degree days models and runs on Excel software with input data, such as insect pests information, Weather information, and levels to forecast the insect/disease. This model assesses how favourable weather conditions are for each organism species and how severe each disease may be. The growth of an organism calculates by an IF function in Excel software. In addition, forecasts based on the current surveying, history field, varieties, stage growth of tobacco, the experience of the predictor, and biology of insect pests to decide a final prediction result and give some good controls. Some predicting levels: 0: No active; 1: Active and negligible damage; 2: Active and light damage; 3: Active and moderate; 4: Strong action and severe damage.

Disease and insect information	
T	Temperature levels for infection and growth of insects and diseases: Tbase, TU, and Topt.
DD	Degree days of insects (Frank G Zalom et al., 1983).
ADD	Accumulated degree-days of insects
RH	Relative humidity for infection and growth of pests
P	Predict (P) the daily severe rating of disease/insect from 0 (no damage) to 4 (severe damage)
Weather information	
T_{max}	Daily maximum Temperature.
T_{min}	Daily minimum Temperature.
T_{av}	Daily average temperature
Prec	Daily precipitation
RH	Daily average Relative Humidity.
Weather	Cloud, overcast, rainy, sunny, wind
LW	The total number of leaf wetness hours a day.

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Levels to forecast the insect/disease

IF function: IF (Humidity is dry) and (Temperature is very low) and (Leaf wetness duration is short) and (Average Temperatures during those wet hours is very low) and (compared to growth conditions of pests) then (Disease/insect is no active);

- IF function: IF (Humidity is dry) and (Temperature is low) and (Leaf wetness duration is short) and (Average Temperatures during those wet hours is low) and (compared to growth conditions of pests) then (Disease/insect is no active);

……...;

- IF function: IF (Humidity is high) and (Temperature is optimal) and (Leaf wetness duration is long over leaf wetness hours that optimal growth of disease) and (Average temperatures during those wet hours is optimal) and (compared to growth conditions of pests) then (Disease is very strong action and causes severe to very severe damage/insect is low action);

- IF function: IF (Humidity is a medium level) and (Temperature is optimum) and (Leaf wetness duration is very short or no leaf wetness) and (compared to growth conditions of insect pests) then (Disease is no active/insect is very strong action and can causes severe damage).

3. Resutls and discussion

3.1. Biological information of the tobacco budworms and aphids

Data in Table 1 shows that the tobacco budworms can only appear, develop, and harm when the temperature increases in the range of 13.3 - 33°C. The optimum temperature ranges from 22 - 24°C for larvae and 21 - 27°C for E, A, F, and P. When the temperature is lower than 13.3°C and above 33°C, insects can not be active. The growing relative humidity ranges from 50- 100%, and optimal humidity ranges from 80 - 85%. Those optimum elements are the same study results of Wu & Guo, 1996; Li, Zheng & Tang, 2016; Gao & Zhai, 2010. When RH < 70%, especially under 63%, the mortality rate of larvae is up 96.15%, and all pupae can not mature; T ≥ 30°C, the mortality rate of the 1st instar larvae is up to 82.76% (Nguyen Van Chin, 2011). Tobacco budworms enter diapause at a constant temperature of 15°C and above 33°C that reduces in both males and females, especially in females (Kurban, A., 2007; Mironidis, G et al., 2012; Liu Z et al., 2004). Degree days play an important role in the growth of tobacco budworms in the field, especially some generations appearing on tobacco. Base development temperature (Tbase) and Upper development temperature (TU) are 13.3°C and 33°C, respectively. To complete the life cycle of tobacco budworms, they accumulate growing degree days of 413.3°D.

Growing temperature levels of tobacco aphids increase in the range of 4.9 - 32°C, humidity from 60% to 100%, and optimal temperature and RH levels range from 20 - 25°C and 80 - 85%, respectively. When temperature and RH are lower than 17°C and above 30°C, RH < 70% lead to the activity of aphids strongly decreases; the temperature and RH are lower than 4.9°C and above 32°C, RH < 60%, aphid activity can not be active. Tbase and TU are 4.9°C and 32°C, respectively. To complete a life cycle, aphids need to accumulate 130°D. According to a study by Samdur, M.Y et al., 1997, the average maximum relative humidity of 85 to 88% is the most congenial condition for an increase in aphid population; RH = 75 to 85%, it is favoured aphid multiplication, RH < 65%, the activity of the aphid ceases (Kulat, S.S.,1997). The pest incidence decreases quickly when the temperature is above 35°C, RH < 60%, and rainfall of 10 mm per day (Rohilla, H.R et al., 1996; NARJARY et al., 2013).

Table 1. The growing conditions of tobacco budworms and aphids

Insect information	Forecast levels				
	0	1	2	3	4
Tobacco budworms					
The gowing temperatures of E, A, F, P (°C)	≤ 13,3; ≥ 33	13,3 - < 18 > 30 - < 33	18 - < 21 > 27 - ≤ 30	21 - 27	21 - 27
The gowing temperature level of L (larvae) (°C)	≤ 13,3; ≥ 33	13,3 - < 18 > 30 - < 33	18- < 22 >24 -< 30	22 - 24	22 - 24
T ≥ 30°C, mortality rate of the one instar larvae is up to 82.76% [Nguyen Van Chin, 2011], the most budworms enter diapause at T < 15°C, > 33°C.					
Relative humidity (RH) %	50	60	>60 - < 75 > 90 - 100	75- < 80 > 85 - ≤ 90	80 - 85
RH≤ 63%: Mortality rate of larvae is up 96.15% and all pupae can not mature% [Nguyen Van Chin, 2011].					
[1]ADD (egg – adult): 413.3°D, Base development temperature (Tbase): 13.3°C, Upper development temperature (TU): 33°C [Butler et al., 1976]					
Tobacco aphids					
The gowing temperature level (°C)	< 4.9; ≥ 32	4.9- < 17 > 30 - < 32	17 - < 20 > 25 - ≤ 30	20 - 25	20 - 25
Relative humidity (%)	60	70	70 - < 80 > 95 - 100	85 - 95	80 - 85
ADD (1instar – adult): 130°D, Base development temperature: 4.9°C, Upper development temperature: 32°C [Whalon et al., 1979]					

3.2. Forecast the tobacco budworms and aphids in Cao Bang region

3.2.1. Forecast the tobacco budworms

To predict the tobacco budworms appearing in the field, we estimate the impacts of the weather and climate conditions on the growth and development of insects by two models. Those are the Degree-Days model (figure 1) and the weather model (figure 2). The final forecast is synthesized from the Degree-Days model and the weather model.

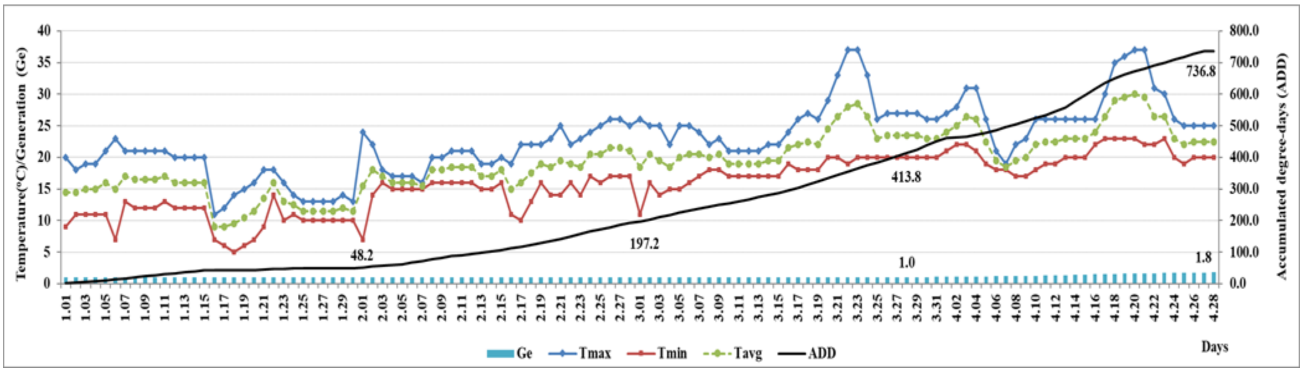

Figure. 1: Forecast the generations of the tobacco budworms following Degree-Days in Cao Bang region from 01 January to 30 April, 2023

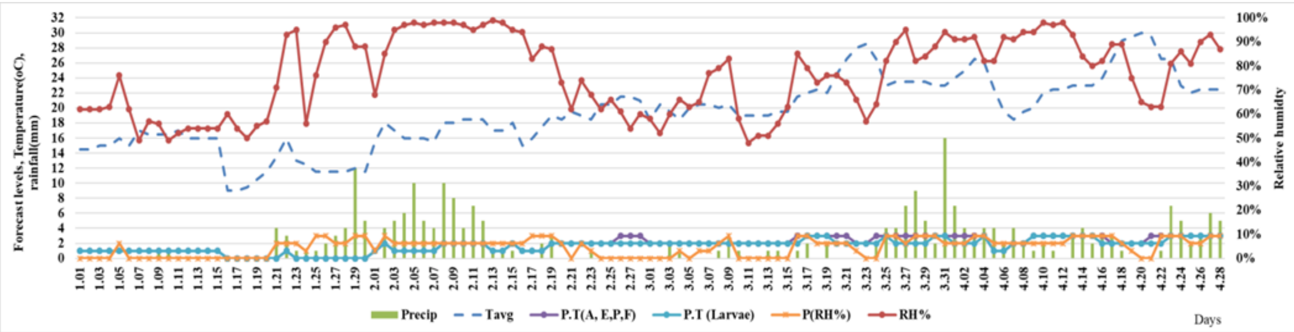

Figure. 2: Forecast the growth of Tobacco budworms following Temperature, Rainfall (Precip), Relative humidity in Cao Bang region from 01 January to 30 April, 2023

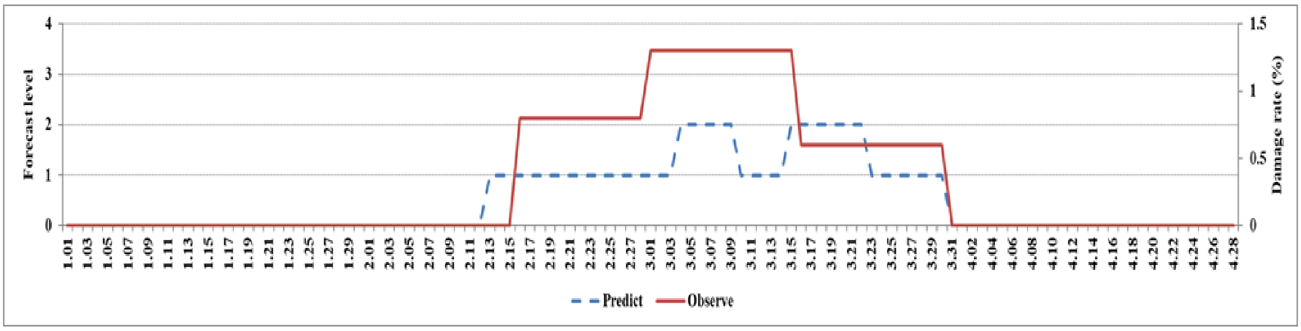

Figure. 3: Forecast and observe the budworms in the tobacco field in Cao Bang region from 01 January to 30 April, 2023

Predict the tobacco budworm using Degree days: Since insects are cold-blooded animals, temperature plays a major role in their growth and development. Each insect has a temperature threshold and can not develop when temperatures are below or above. Insects also have an optimum temperature range in which they grow fast. Then, there is the maximum temperature (termed upper cut-off) above which development stops. Those predict insect activity and the appearance of symptoms during the growing season. Degree days of insects calculate by the number of degree days on a specific day. One-degree day results when the average temperature for a day is one degree over the threshold temperature (Ric Bessin and Raul Villanueva, 2019). Degree-day (°D) calculated between *Heliothis virescens* (F.) population peaks of adult males and between larval infestation peaks on tobacco in Florida (F. C. Tingle and E. R. Mitchell, 1988), a measure of thermal accumulation that provides a mechanistic link between climate change and species phenology. Degree-day models, because of their prediction accuracy over the ordinal dates, are considered important analytical tools for predicting developmental events in plants and insects (Higley, L. G, 1986). Degree-day models estimate the temperature-dependent life processes and developmental thresholds through a fitting of several linear and non-linear mathematical functions of higher biological significance (Sharpe, P. J. H et al., 1977). The heat units (DD) are accumulated between the established lower and upper threshold temperatures (Tbase and TU) over the time interval for the developmental event of interest in the species' life history, e.g. development from egg to adult in insects (Peddu, H et al., 2020).

To complete a tobacco budworm's lifecycle, growing degree-days of tobacco budworm have to be accumulated 413.3^{o}D. Based on accumulated degree days will determine how many generations occur and estimate the harmful level of tobacco budworms. According to evolutionary temperature and DD from January to April 2023 in the Cao Bang in Figure 1, Degree days accumulate 736.8^{o}D and correspond to one to two generations occurring in the field. For example, from January to March, DD reaches 413.8^{o}D and corresponds to a life cycle. Detailing as the average temperature in January is 13.7^{o}C (Tmax: 17.3^{o}C and Tmin: 10.2^{o}C), equal to the base development temperature (13.3^{o}C), and accumulated degree day reaches 48.2^{o}D; in February, the average temperature is 18.1^{o}C (Tmax: 21.3^{o}C and Tmin: 14.8^{o}C), and DD: 149.2^{o}D; March: the average temperature: 22^{o}C and DD: 216.6^{o}D (Tmax: 25.9^{o}C and Tmin: 17.9^{o}C); and April, the average temperature: 24^{o}C and DD: 323^{o}D (Tmax: 27.6^{o}C and Tmin: 20.4^{o}C). From the above analysis results, forecast the budworms only cause negligible to mild damage in the spring crop of 2023.

Predict the tobacco budworm using Weather, climate elements: Abiotic factors, such as temperature, humidity, photoperiod, wind speed and rainfall, play important roles in determining the geographic distribution and population dynamics of insect species, as well as the diel periodicity of individuals (Pellegrino AC et al., 2013), especially the temperature, humidity, and rainfall. Based on the interaction between the weather factors, biological characteristics of insects, and the growing stage of tobacco to forecast the growth, development, and harmful ability of insects in the field. The forecast results of tobacco budworm in Figure 2 from January to April in Cao Bang province show, in January, the temperature and relative humidity are very low, with the average temperature being 13.7^{o}C (T= 10.2 - 17.2^{o}C) and average relative humidity being 66.4% and dry air condition. Those factors are not favourable for the growth and occurrence of budworms in the field. Specifically, the average relative humidity from January 01 - 20th is 57% and dry air condition (49 - 63%) is not suitable for the growth of budworms, and the mortality rate of the first instar is very high because they cannot moult into 2nd instar and the pupae do not mature to change into adult (Nguyen Van Chin, 2011); From January 16 - 30, the average temperature is 11.6^{o}C (T= 9 - 13.5^{o}C) and under Tbase = 13.3^{o}C leading to the budworms is no active, because all insects enter diapause at a constant temperature of 15°C (Mironidis, G et al., 2012; Kurban, A et al., 2007). In addition, from 21 – 30 January, rainy prolongs many days with average daily precipitation of 3.6 mm (1 - 12mm), leading to increasing relative humidity (91%) and soil water content. Prolonged periods of rain and high humidity result in the death of *H. armigera* (Ge F et al., 2003), increase the deadly rate of pupae in soil (Chen FJ et al., 2003), decrease capable flight action, copulation, and fecundity of butterflies (Wu KM and Guo YY, 1996; Li Z et al., 2016).

Based on the above data, predicting tobacco budworms will be no action in January. From 1 - 15 February, it continues to rain for many days with an average rainfall of 4.7 mm and relative humidity ≥ 96%, which is not suitable for the action of insects. In this stage, the average temperature of 17.2^{o}C (15.5 - 18.5^{o}C) reduces rapidly the growth of tobacco budworms. According to study results, pupae of budworms can remain in diapause for at least 20 months at 18°C (Phillips, J.R. and L.D. Newsom, 1966), the fecundity of *H. armigera* decreases strongly when the temperature is under 20^{o}C and the lowest at ≤ 15^{o}C (Noor-ul-Ane, M et al., 2018). Continuous rain time from 21 January to 19 February is not appropriate for the activity of adults, such as capable flight action, copulation, and fecundity. Adult emergence reduces in extreme wet environments and wet soil. The mortality rate of adults is high when heavy and prolonged rain. From 20 February to 24 March, average relative humidity is low and dry, under 65% (RH= 48 - 76%) is not suitable for the strong growth of budworms, even though the average temperature at 21^{o}C (T= 18.5 - 28.5^{o}C). At 21^{o}C, it is favourable for the development of tobacco budworms. So predicting the tobacco budworms will be active and cause negligible harm. From 25 March to 30 April, most days appear a little heavily rainy, especially from 27 March to 7 April, 13 - 17 April, and 23 - 30 April, with rainfall of 80 mm and average relative humidity of 80 - 98% that strongly reduce the population of the budworms in the field, especially the most adults and pupae will be dead. On the other hand, from April onward, tobaccos are topped and treated the shoot by Accotab 330EC, leading to reducing the harm of budworms. So predicting in April, tobacco budworms will be occurrence, but with no damage or cause negligible harm, even though the average temperature of 24^{o}C is appropriate for the growth of budworms.

In the tobacco growing region of Cao Bang, tobacco plants quickly develop the stems and leaves, and only one generation of budworms in the field from January to March. April onward, tobaccos are topped, treated the shoot, and begin the harvest leading to little attraction to the tobacco budworms.

Based on all data above, we predict the tobacco budworms causing negligible to light harm in the spring season of 2023, detailing: they are not active or active no damage in January; February to March: Budworms occur and cause negligible to light harm, and April: Budworms cause no harm and very light harm. The observational results of the tobacco budworms in the field are proper for predictive goals: Budworms cause negligible harm from 15 February to 30 March with a damage rate of 0.6 - 1.3% (Figure 3). Control methods: Treating them by hand and not controlling the with pesticides.

3.2.2. Forecast the tobacco aphids

Predict the tobacco aphids using Degree days: Tobacco aphids are one of the important pests of tobacco, and the best temperature of aphids is about 22°C, with most activity occurring during the warmer months. Lower and upper-temperature thresholds of aphid development are at 5°C and 35°C, respectively (PA. Edde, 2018). The aphid population corresponds to weather parameters, such as maximum, minimum and mean temperature, relative humidity, saturation deficit and total rainfall (Prasad, S.K et al., 2000). The growth of insects occurs under optimal temperature levels. If insect exposes to extremely low or high temperatures, the growth rates of the insect will reduce, reproduction fail, and if it exposes sufficiently long enough, death will occur (Andrewartha and Birch 1954). High temperatures affect aphids by reducing respiration, increasing water loss, and accumulating waste products (Lamb,

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1961). The increased temperature will increase accumulative degree days leading to an increasing aphid population and generations. Using the accumulated degree days is quite successful in explaining the generations of *M. persicae*. The thermal unit accumulations (DD) means to forecast the population peaks and generations of aphids and many insects. According to Figure 4, the total accumulated growing degree days from January to April 2023 in the Cao Bang region reaches 1626.1^{o}D, corresponding to about 12 - 13 life cycles (generations), and in April, population and generation peaks are 4 - 5 generations. The growing stages of tobaccos in Cao Bang that are damaged severely by aphids are from February to March when tobaccos grow and develop strongly about stem and leaf with 8 - 9 generations. In January and April, populations of aphids reduce very quickly because it is cold, harmful cold in January; in April, the tobaccos are topped, treated the shoot by accotab 33EC and matured, leading to being unfavourable for growth and damage of aphids.

The observational results in the field show the damage rate of aphids on the tobacco is low, population peak of ≤ 5% and low density on the leaf in March. Detailing as in January, aphids only are scattered occurrence with adults with wing; February to March: Aphids appear and cause negligible harm, the most are wingless, with an incidence of 5%; and the April, aphids are little occurrence in the tobacco. So there are differences between forecast and observation results about damage level. Following the forecast, aphids will cause severe damage from March to April, but the observative result is negligible harm by aphids. This difference is the fluctuating temperature conditions. For example, daily fluctuating temperature levels of January range from 5 - 21^{o}C, Taverage daily max: 17.5^{o}C and Taverage daily min: 10^{o}C, etc. According to J.A. Davis et al., 2006, this model (growing degree days) only predicts accurate levels when fluctuating temperatures are low and at optimal fluctuating temperature conditions, especially the most favourable fluctuating temperature conditions - optimal developmental thresholds. The fluctuating temperatures extend threshold limits, and the accurate level of prediction is low (Messenger 1964). Degree-day models are accurate when temperatures fall within the lower and optimal developmental thresholds. When temperatures go beyond the optimal temperature, the degree-day model will not work, unsuitable for predicting insect development. Degree day model tends to underestimate the growth of populations at high temperatures (Elliott and Kieckhefer, 1989), and simple heat unit summations are not well correlated with population growth at high temperatures (Tamaki et al., 1982). The constant temperature development model failed to predict development under fluctuating temperatures (J.A. Davis et al., 2006). Temperatures increase above upper or lower optimal thresholds, the growth of insects slows, and fecundity and longevity are reduced (Newman, 2005).

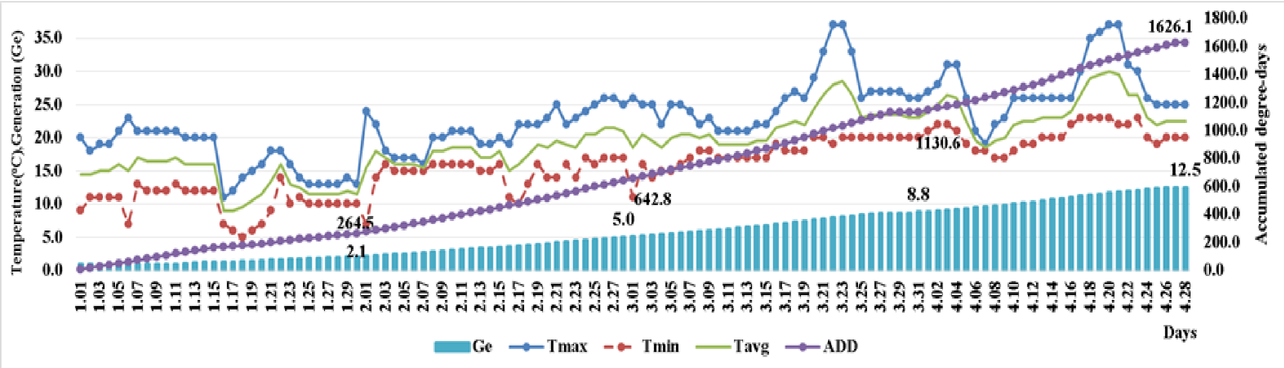

Figure 4. Forecast the growth of the tobacco aphids following Degree-Days in Cao Bang region from 01 January to 30 April, 2023

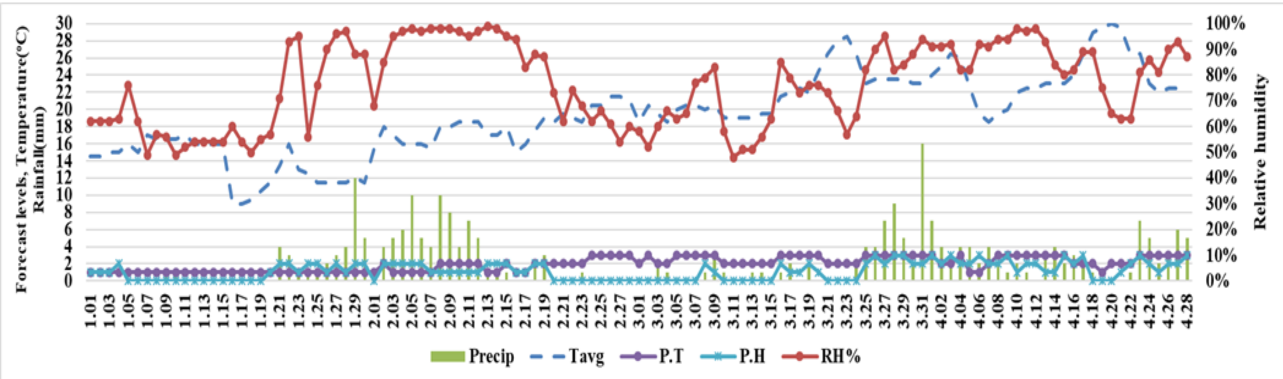

Figure. 5: Forecast the growth of Tobacco aphids following Temperature, Rainfall (Precip), Relative humidity in Cao Bang, 01 January to 30 April, 2023

Predict the tobacco aphids using Weather, climate elements: Weather factors play an important role in the growth, development and damage of aphids in the field. There are four elements to use for the forecast model, such as temperature, relative humidity, rainfall, and stage of the growing tobacco. The forecast results in Figure 5 shows that the tobacco aphids will be active and causes negligible harm from January to April 2023 in the Cao Bang region. In that, in January, the tobacco aphids will be active but with no damage because the average temperature in January is 13.7^{o}C, and the average min temperature is 10.7^{o}C. The temperature levels are low in

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January and are unfavourable for growth, fecundity, migration of adults, etc. For relative humidity, it is too low, ranging from 49 - 65%, average humidity of 57.1% from 01st - 20th January; From 21 - 30th January, it continues to rain for many days with rainfall of 1 - 12 mm, with an average precipitation of 3.6 mm per day. With humidity and rainfall of January are not proper for the growth, development, action, flight, and damage of aphids. From 01st - 20th February, it occurs rainy and high relative humidity for many days, with an average rainfall of 4.2 mm per day and RH = 85 - 99% (average humidity of 94%), in addition to an average temperature of 17.1°C, especially the night temperature reduces down 14°C. Those limit the active ability of aphids, such as flight, move, and increase mortality rate and rapid reduction of populations by rain and high wind speeds on some days that wash away the aphids. From 21th February to 24th March, the relative humidity is very low, it is dry, with little rain, with RH ≤ 64.4%, leading to being unfavourable for the growth and development of aphids, and the activity of the aphid ceases, even though the temperature is suitable for the growth of aphids (average temperature of 21 - 22°C, average max temperature of 25 - 26°C and average min temperature: 16 - 17°C), and tobacco plants are growing strongly about stem and leaf. From 25th March to 30th April, it rains for many days (32 days), with rainfall of 128 mm and an average of 3.5 mm per day. Rain for many days that increases the relative humidity (86 - 88%) affects the development of aphids and increases the infection incidence for aphids. Rain for many days reduces the rapid population density of nymphs of aphids. The addition to the stage of tobacco plants in the field is appropriate for the rapid growth of aphids. The tobaccos are topped and treated the shoot and begin the harvest, and the leaf is mature, which is unfavourable for aphid damage.

Weather conditions have a lot of variation, the higher or lower than the optimal thresholds of tobacco aphids lead to a decrease in the efficiency of insect prediction according to the Degree-days model. Application of both Skybit and Fuzzy models has a higher predictive accuracy for the aphids. Evaluating the growth of the aphid in the field is suitable for many studies by many authors. The most activity of aphids occurs during the warmer months, and the best temperature is about 22°C Peter A. Edde, 25°C±1°C Tiwari et al., 2018, 20 and 25°C (Akca, I. et al., 2015), peak aphid population reached 18°C and the peak at 20 - 22°C (B. NARJARY et al., 2013). The intrinsic rate of increase of aphids is lowest at 17°C (Baral S et al., 2022). Aphids can not fly if the temperatures are lower than the range of 13-16°C (Irwin, M. E et al., 2007). The development rate during the pre-reproductive period diminishes to around 15°C (Duffy, C et al., 2017). The aphid population growth is negatively related to the moisture factors (precipitation and humidity). The average maximum relative humidity of 85 to 88% is the most congenial condition for an increase in aphid population (Samdur, M.Y et al., 1997), 75 to 85% for the favoured aphid multiplication, and RH ≤ 65%, the activity of the aphid ceased (Kulat, S.S et al., 1997). The rapid decline of the population when it rains. Especially the heavy precipitation and very high wind speeds for many days wash away the nymphs of aphids (B. NARJARY et al., 2013). The forecast model established by statistical methods has an accuracy of 73% - 82% for the emergence period, peak period and damage degree (Liu Ming-chun et al., 2009).

Based on all data above, we predict that tobacco aphids are active and cause negligible harm levels in the spring season of 2023 in Cao Bang. The observational results of the aphids in the field also cause very light harm levels, with a damage rate under 5% and low density. Control methods: Continuing observation of the tobacco aphids in the field and no control of the aphids by pesticides.

3.3. Forecast the tobacco budworms and aphids in Tay Ninh region

3.3.1. Forecast the tobacco budworms

Predict the tobacco budworm using Degree days: For the Degree Day model, temperature plays an important role in growing population peaks of insects from egg to adult. Based on DD to forecast the populations and generations in the tobacco field. The result of Figure 6 shows that for the Tay Ninh region, it's the weather is hot and sunny from the stage of transplanting to harvest (5 - 10 December, 2022 (transplanting time) to 15 April, 2023), especially some days have max daily temperatures are above 33°C (TU = 33°C). The growing degree days accumulate from 15 - 30 December, 2022 to 15 April, 2023 are 1909.5°D and correspond to 4 - 5 generations in the field. The rapid growth and development stage is from 16 December, 2022 to 14 February, 2023; From 15th February onward, tobaccos are topped, treated shoots, and begin the harvest. So the tobacco budworms only cause severe harm from 16th December, 2022 to the previous topping when tobacco plants grow and develop quickly about the stem and leaf, but only occur two generations in the field, leading to the tobacco budworms causing negligible harm. From 15 February onward, tobacco budworms are active and have no damage. The tobacco budworms do not increase rapid population peaks and generations on the tobacco plant because average temperature levels are higher than the optimal temperature levels of the budworm, leading to reducing accumulated degree days. For example, average temperature levels from 16th December, 2022 to 30 January, 2023 are at 27.4°C compared to the optimal temperature levels of the budworms of 22 - 24°C, February: 28.6°C, March: 29.7°C, and April: 30.1°C.

Predict the tobacco budworm using Weather, climate elements: Temperature, relative humidity, and sunny are effect factors that influence the growth and flight of the adults, larvae, and pupae. The temperature levels that range from 27.4 - 30.1°C from December, 2022 to April, 2023, compared to the optimal temperature levels of the budworms of 22 - 24°C or to 25°C, reduce the growth of adult, larvae, and pupae in the field, lead to tobacco budworms only cause negligible to light harm, no ability for fast growth of budworms (Figure 7). Especially the max average temperatures in Tay Ninh are higher than the upper temperature. For example, from December, 2022 to January, 2023, max average temperatures are at 31°C, 33.3°C in February, 35.2°C in March, and 35°C in April. According to many authors, the most favourable temperatures for a moth's flight range from 20°C to 22°C (Gao, Y. B et al., 2010), 20°C to 24°C (Wu, K. M et al., 1996), 25 - 28°C (Gao, K. H et al., 2007). When the temperature is higher than 33°C, diapause will happen. Sixth-instar and prepupal larvae are sensitive stages to hot conditions (Liu, Z et al., 2016); the temperature reaches 33°C, diapause ratios significantly increase (Liu, Z. D et al., 2004); temperatures decreasing from 25 - 28°C is favourable for the activity of adults (Morton, R et al., 1981, Huang J et al., 2020); ≥ 35°C, the fecundity of *H. armigera* decreases very quickly. Total fecundity increases with increasing temperatures up to 25°C, then decreases sharply at 37.5°C (Noor-ul-Ane, M et al., 2018); the early death of *H. armigera* at higher temperatures than 35°C.

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Relative humidity has an important role in the growth of adults, the moulting of larvae and pupae, etc. The optimal relative humidity of tobacco budworms is 80 - 85% or 90% when humidity is lower or higher than the optimal relative humidity to reduce the growth and development of tobacco budworms. Following the data of Figure 7 show that the weather in the Tay Ninh region in season 2023 is little rain and dry - low relative humidity, with an average relative humidity of December, January, February, March, and April are 50%, 52.4%, 48.3%, 39.6%, and 46.5%, respective. Those weather conditions are not suitable for the growth of budworms, such as the moulting of 1st instar and 2nd instar and pupae. The average relative humidity is low and dry in season 2023, under 65%, which is not suitable for the strong growth of budworms. Because relative humidity mainly affects water within the insect body to produce effects on insects, viz., affecting water balance within the insect body. Moisture influences insect life cycles via one or more three mechanisms - as a token stimulus for diapause, modulator of developmental or reproductive rates, or behavioural cue for seasonal events (Maurice J et al., 1998). Changes in RH can affect water fluctuations in host plants and further impact the feeding of insects (Qin, J. D, 1964). Dry soil prevents the rate of adult eclosion occurring in field conditions (Johnson S.N et al., 2010); Dry soil moisture promotes prolonged diapause in already diapausing individuals of *S. mosellana* (Cheng W et al., 2017). The most suitable RH for *H. armigera* is 70% - 85% when dry soil and medium to low relative humidity (≤60%) prevent the emergence of adult *R. pomonella* (Trottier R et al., 1979). Low humidity makes the eggshell a more difficult obstacle for larvae to chew their way out, affecting the formation of the initial population. Low humidity reduces the vigour of larvae and hence reduces their ability to cause damage (Jin, C. X 1979).

Based on all data above, we predict the tobacco budworms are active and cause negligible harm in Tay Ninh in season 2023. The observational results of the budworms in the field cause very light harm levels, with a damage rate under 1%. Control methods: Continuing observation of the and no control of by pesticides.

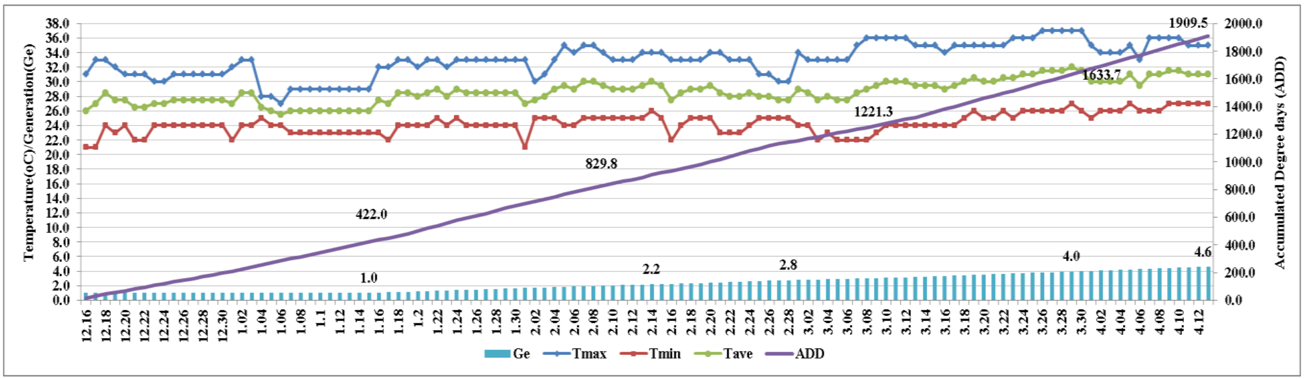

Figure. 6: Forecast the growth of the tobacco budworm following Degree-Days in Tay Ninh region from 15th December to 15th April, 2023

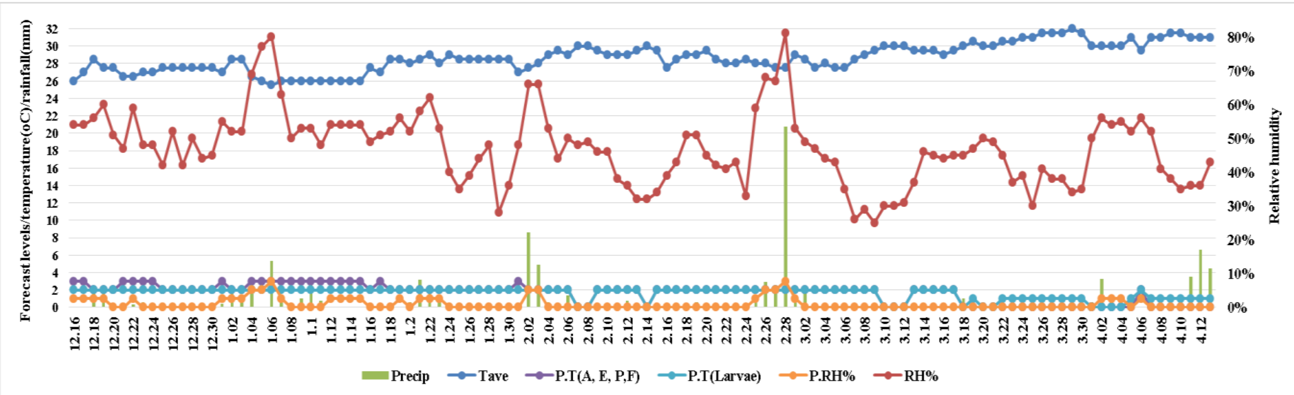

Figure. 7: Forecast the growth of the tobacco budworms following Temperature, Rainfall (Precip), Relative humidity in Tay Ninh region from 15th December to 15th April, 2023

3.3.2. Forecast the tobacco aphids

Predict the tobacco aphids using Degree days: The results of Figure 8 show that accumulative degree days from 16 December, 2022 to 15 April, 2023 reach 2779.5^{o}D and correspond to 21 - 22 generations (Figure 8), in that 10 - 11 generations occur in the stage of rapidly developing tobacco plants about the stem and leaf. According to the degree days model, the tobacco aphids will rapid development for the population peaks and damage severe harm to the tobacco in Tay Ninh. But the observation results show that aphids cause harm with an incidence of under 1% and cause negligible damage. Similar to forecast the aphids in Cao Bang, using this model is little effect in predicting the damage rate of the aphids in the field in Tay Ninh. Because the daily fluctuating temperature levels are higher than the optimal developmental thresholds of aphids. The fluctuating temperatures extend threshold limits, and the accurate prediction is low. Predicting the degree-day models is accurate when temperatures fall within the optimal developmental thresholds. When temperatures go beyond the optimal temperature, degree-day models can not work, unsuitable for predicting insect development. For example, average temperature of December, 2022 to January, 2023 is about 27°C, February: 29°C which reduce the rapid growth of the aphids; Especially the March and April are hot, with temperature at about 30 - 31°C, and max daily temperatures are above 35°C lead to inhibit the development of aphids (TU = 32°C),

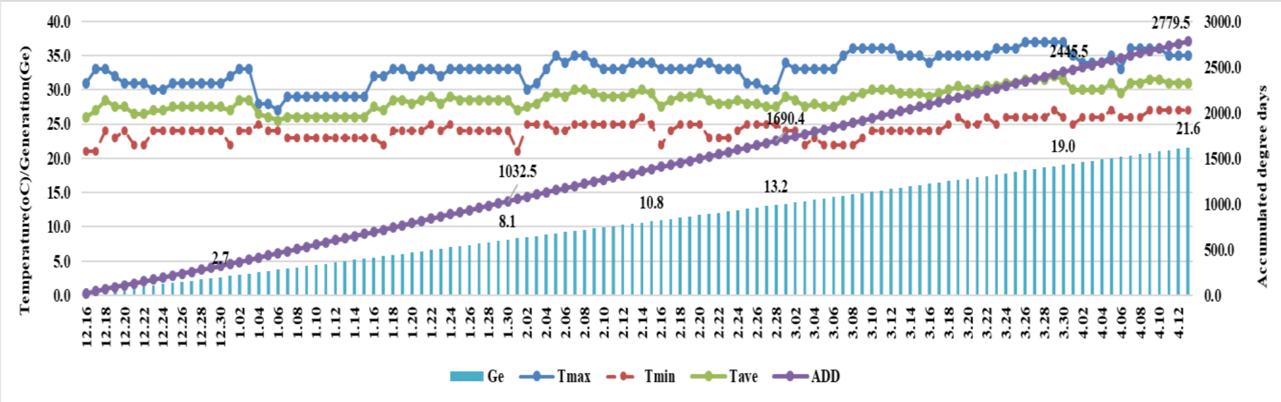

Figure 8. Forecast the growth of the tobacco aphids following Degree-Days in Tay Ninh region from 15th December, 2022 to 15th April, 2023

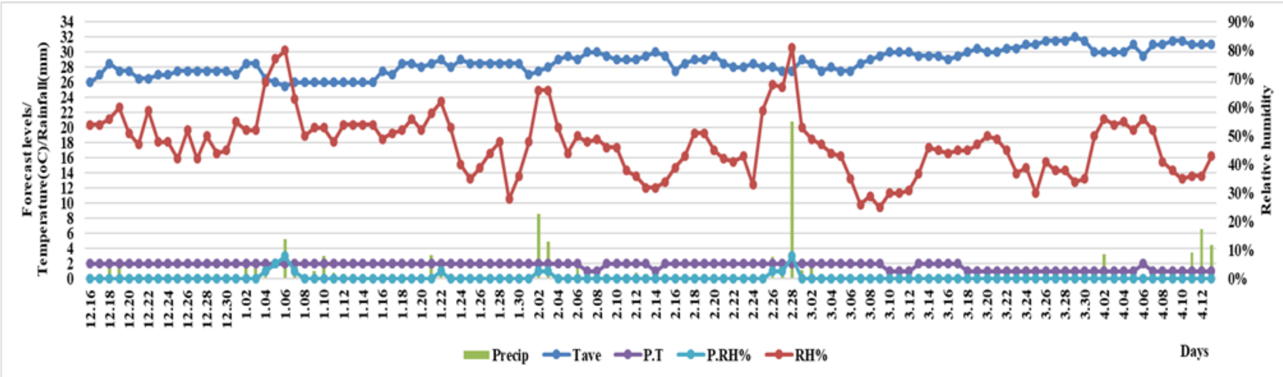

Figure 9. Forecast the growth of the tobacco aphids following Temperature, Rainfall (Precip), Relative humidity in Tay Ninh region from 15 December to 15 April, 2023

***Predict the tobacco aphids using Weather, climate elements**:* The predictive results of Figure 9 following the temperature show that tobacco aphids only occur and damage from negligible to low harm levels, with a forecast level of 1 - 2, and no ability to develop quickly and severe harm in the tobacco. The aphids cause negligible damage because the average temperature from December, 2022 to January, 2023 at 27°C and February at 29°C reduce the rapid growth of the aphids. Especially from March and April are hot, and the temperature about 30 - 31°C, and max daily temperatures above 35°C inhibit the development of aphids (TU = 32°C), especially the impact on the growth of winged and nymph. When the temperature is upper 31°C, aphids are not able to action (Irwin, M. E et al., 2007); the Fecundity rate of aphids decreases quickly at ≥ 27 (Nihal Özder et al., 2013). An increased temperature of 28°C is a negative effect on the biology of *M. rosae* by shortening the period of reproduction and longevity, thus reducing the demographic parameters and fecundity, and when a temperature close to 30 °C is lethal. Aphids gave birth to the lowest at 28 °C. The population of *M. rosae* decreases quickly at 28°C (Dampc J et al., 2021). A temperature of 28 °C and above the thermal optimum has a negative effect, limiting population development and growth (Durak R et al., 2020). An increase in temperature above the thermal optimum in *Myzus varians* can not reach maturity and do not give birth to nymphs (Chiu M.C et al., 2012), the low survival rate of aphid nymphs at high temperatures (Ohtaka C et al., 1991). An increase in temperature up to thermal optimum not only causes disturbances in the development of aphids and lowers their longevity, fecundity, and demographic parameters but also disturbs the mutualism between the aphids and their symbionts (Chiu M.C et al., 2012). The high survival rate is until 24°C, and after 24°C, the survival proportion of nymphs is scaling down (Duffy C et al., 2017), and above 30°C, nymphs will be died before finishing their development (Dean G. J et al., 1970).

The aphid population growth is positively related to the atmospheric temperature and sunshine hours but is negatively relative to the moisture factors, such as precipitation and humidity. If heavy rain washes all aphids out in tobacco and rain for many days increases the relative humidity that affects on growth of aphids. Aphids are in rapid development when humidity ranges from 80 - 85%. When relative humidity is under 65%, the activity of the aphid is ceased (Kulat, S.S et al., 1997). According to Figure 9, the low average relative humidity in season 2023 is about 47.1%, including the relative humidity of December is at 50.1% (42 - 56%), January: 50.4% (28 - 80%), February: 48.3% (33 - 68%), March: 39.6% (26 - 50%) and April: 46.5% (36 - 56%). The low relative humidity is unfavoured for the growth of aphids in the field in the Tay Ninh region. So for aphids, relative humidity plays an important in the development of aphids. Low humidity inhibits the growth of aphids, and aphids will not occur in the field. Following the study

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results of V. L. Pathipati et al., 2020 in the field condition, when the relative humidity is under 50%, aphids do not occur in the field, especially humidity of all day (night and day time) is under 50%. The aphid population decline corresponds to the mean maximum temperature of 35°C and relative humidity of 54%, respectively (Rashid Ahmed Khan et al., 2020). Heavy rain for continuous days washes aphids out of the leaf. In the months of season 2023, rain for many days with heavy rainfall and strong wind. For example, on the 01 - 06 of January, rainfall range from 1.4 - 5.3 mm, 2 - 3 and 26 - 28 of February: 5 - 9 mm and 3 - 21 mm, the 11 - 13 of April: 4 - 7 mm.

Based on all data above, we predict the tobacco aphids are active and cause negligible harm in Tay Ninh in season 2023. The observational results of the aphids in the field cause very light harm, with a damage rate under 1% and density's low. Control methods: Continuing observation of the aphids and no control of the aphids by pesticides.

For the forecast of the aphids in Vietnam, the application of the degree days is lower accurate than weather factors because fluctuating temperatures do not fall within the optimal temperature thresholds of aphids. The lower or higher fluctuating temperatures than the optimal temperature thresholds have affected the predictive accuracy. Evaluating the accuracy of the forecast, for the northern province, it reaches the range from 83.4 - 91.7% because the weather factors have extent changed for predictive elements; Southern province, weather conditions have little change, and the accuracy of the forecast is high, reaching close to 100%. To predict the tobacco budworm, the degree days, skybit, and Fuzzy models are used in a model to give the most accurate prediction. For the tobacco aphids, only use the skybit and Fuzzy models in a model.

4. Conclussion

In 2022 - 2023, Vietnam Tobacco Institute applied the degree days, skybit, and Fuzzy models to forecast the tobacco budworms and aphids in the tobacco field in Cao Bang and Tay Ninh regions. Predictive results are accurate for the development of insects in tobacco with an accuracy of 83.4 to nearly 100%. Through the predictive results and observable incidence of insects in the field, Tobacco Institute gives the best control methods to reduce the damage of pests; reduce the use of pesticides compared to years ago; increase yield and quality; and increase income for tobacco-growing farmers.

To accurately forecast the insects in tobacco, the combinable model of Skybit and Fuzzy is the best model for forecast tobacco aphids. For the tobacco budworms, the best model is a combination between degree days, Skybit and Fuzzy.

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Competing interests

Authors have declared that no competing interests exist.

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