On weather affecting to Brown plant hopper invasion using an Agent-based model

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ABSTRACT
In this paper, a new agent-based model is proposed to model and simulate visually growth and invasion of brown plant hoppers in different localities and at different times under effects of weather conditions such as temperature, humidity, rainfall and wind factors. The results from simulation are validated with light traps data collected in communes in the Mekong Delta region and show that brown plant hoppers life is affected by weather.

Keywords
Brown plant hopper (BPH); BPH growth; BPH invasion; Agent-based model; GAMA platform

1. INTRODUCTION
Brown plant hopper that is one kind of Nilaparvata lugens species is known as the major pest on rice, this insect damaged rice crop systems in Asia [7] and is known as carriers of rice virus-related diseases: grassy stunt, ragged stunt and wilted stunt, these viruses cause hopperburn [4]. In 2006, the agricultural ministry in Vietnam reported a loss of 700000 tons of rice [8] and this leads to the limitation of rice exports. How to know the population dynamics of brown plant hoppers and predict target areas that BPHs can invade is still a complex problem facing the Mekong Delta region, Vietnam.

In this paper, we propose a new model combining agent-based model (ABM) and geographic information system (GIS) environment to attempt simulating impacts of weather factors such as temperature, humidity, rainfall and wind to BPH population density and invasion. This model could help users carry out visually different scenarios to understand BPH growth and invasion process. This study is experimented in small areas of the Mekong Delta region and we hope this model could serve as a decision support system (DSS) to help scientists and farmers have a closer visual look on BPH invasion.

The paper is structured as follows: Section 2 presents related works on affects of weather factors to BPH population dynamics, Section 3 analyzes impact rules of weather like temperature, humidity, rainfall and wind to the BPH growing and invading processes. Section 4 designs agents including brown plant hopper, GIS map data, weather factors and their interactions in GIS environment, Section 5 proposes experimental scenarios and evaluates simulation results before a conclusion is drawn.

2. RELATED WORK
A taxonomy and biology [9] classified species of Nilaparvata lugens in the Oriental-Australian regions and countries in Asia. This study showed that the temperature factor affected to egg and nymphal stage, number of BPH females, BPH migration and flight of adults. The effects of climate factors on brown plant hoppers in tropic regions [7] including temperatures between 25 and 30°C, a range of 70 to 85% relative humidity are normally optimal for BPH development. Besides, annual monthly average temperatures from 1954 to 2007 in Jiaxing, China [3] are used to find relationships between BPH development, fecundity, mortality and temperature. The results showed that the temperature factor could be considered as one of reasons leading to BPH outbreaks.

In the Mekong Delta regions, Vietnam, the model [14] analyzed MODIS-based vegetation index to track down the progress of rice varieties and partiton areas that can be infected by plant hoppers, this model applied GIS techniques to identify correlation between climate factors and farming to forecast rice pests outbreaks. Model called BPHSim [12] utilized statistical indicators of BPH density in different growing stages at district scale, agent-based approach and wind factor to modelling BPH invasion on GRID environment. This model did not mention yet other impact rules like temperature, humidity, rainfall. Incorporating BPH's growth and invasion models with GIS environment will help managers decide better policies to prevent potential BPH outbreaks [10].

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3. MODELLING BPH GROWTH AND INVASION WITH WEATHER CONDITIONS

3.1 BPH growth model

BPH life cycle is about 25-28 days for temperature 25-30^{0}C and this cycle includes three growth stages: egg, nymph and adult. After oviposition from 5 to 7 days, BPHs called nymphs undergo five stages within 12 to 14 days and become adults either short winged or long winged. Bionomics of BPHs will be changed according to weather conditions [9][11], the short winged adults occur popularly until rice bloom and at the beginning of harvest the long windged adults develop rapidly to prepare for migrating. Each short winged and long winged female can oviposit 300 and 100 eggs respectively [11].

Temperature has the most important influence to transfer from one growth stage to the other [9][11]. The transferring duration is described in table 1:

Table 1. Duration of transfering stages

		Temp. 25-30^{0}C	Temp. <25^{0}C or >30^{0}C
Egg → Nymph (stage 1)		5-7 days	8-15 days
Nymph → Adult (stage 2)		12-14 days	15-20 days
Adult → Egg (stage 3)	Starting time of obvipositing	3-5 days	3-5 days
	Ending time of life cycle	10-12 days	13-20 days

Percent rates of BPH male and female as well as short winged and long winged adult depend on rice growth stages [11] (table 2):

Table 2. Percent rates of BPH density depend on rice growth stages

Percentage (S_a)	Rice tender (vegetative and reproductive stage)	Ripening Stage
Male : Female	20% : 80%	50% : 50%
Short winged : Long winged	80% : 20%	20% : 80%

BPH mortality rate per day is approximately 3,5% and this rate can be 10% to 15% in case of severe weather [12], especially this rate can reach 30% if rainfall is high [11] in the Mekong Delta (table 3).

Table 3. BPH mortality rate per day

	Rain			
	No	Medium	Heavy	Storm
Mortality rate (R)	3,5%	5%	10%	30%

As referring to results in [11], if temperature is about 25-30^{0}C and humidity is from 80% to 86%, BPH denstity (individuals/m^2) rates after changing to new growth stage are given in table 4.

Table 4. Percent rates of BPH density depend on temperature and humidity after changing to new growth stage

	Temperature: 25^{0}C-30^{0}C Humidity: 80%-86%	Temperature: <25^{0}C or >30^{0}C Humidity: <80% or >86%
Stage 1 (P_e): (Egg→Nymph)	50%	30%
Stage 2 (P_n): (Nymph→Adult)	60%	40%
Stage 3 (P_a): (Adult→Egg)	((Short winged adult x 300) + (Long winged adult x 100)) x 100%	

BPH growth functions in [4] are modified in this paper to determine BPH density at time (t+1) (table 5), variable t is a day:

Table 5. Equations to calculate BPH density in each growth stage

	Growth functions
Number of Eggs	$E(t+1) = [E(t) - E'(t) + E1(t)]*R_e$
Number of Nymphs	$N(t+1) = [N(t) - N'(t) + E'(t)*P_e]*R_n$
Number of Adults	MS + ML + FMS + FML
Number of male short winged adults	$MS(t+1) = [MS(t) - MS'(t) + N'(t)*P_n*S_a]*R_a$
Number of male long winged adults	$ML(t+1) = [ML(t) - ML'(t) + N'(t)P_n*S_a]*R_a$
Number of female short winged adults	$FMS(t+1) = [FMS(t) - FMS'(t) + N'(t)*P_n*S_a]*R_a$
Number of female long winged adults	$FML(t+1) = [FML(t) - FML'(t) + N'(t)*P_n*S_a]*R_a$
Number of new eggs at stage 3	E1(t+1) = FMS*300 + FML*100

where:

-E(t+1), N(t+1), MS(t+1), ML(t+1), FMS(t+1), FML(t+1): number of eggs, nymphs, male short winged adults, male long winged adults, female short winged adults, female long winged adults at time (t+1), sequentially.

-E1(t+1): number of new eggs oviposited at time (t+1) by short winged and long winged adults.

-E'(t): number of eggs obtained in nymph stage at time t.

-N'(t): number of nymphs obtained adult stage at time t.

-MS'(t), ML'(t), FMS'(t), FML'(t): number of male short winged adults, male long winged adults, female short winged adults, female long winged adults are died at time t, respectively.

-R_e, R_n, R_a: percent mortality rate of egg, nymph and adult are died at time t. These rates are supposed to be the same and equal to R (table 3).

-P_n, P_a : percent rate of BPH density after transferring from nymph to adult stage and from adult to egg stage (table 4).

-S_a: percent rate of BPH density depend on rice growth stages (table 2).

To observe easier during simulation, BPH population density in areas is classified into five ranges with different colors (table 6):

Table 6. Coloring for BPH density

BPH density (individuals/m^2)	Color	Level
< 500	rgb[255,255,255]	Normal
>= 500 and < 1500	rgb[200,255,255]	Light infection
>= 1500 and < 3000	rgb[100,200,150]	Medium infection
>= 3000 and <=10000	rgb[200,150,200]	Heavy infection
> 10000	rgb[255,0,0]	Hopper burn

3.2 BPH invasion model

Finding out target areas that BPH groups disperse in this paper are based on three factors: wind direction, speed and invading time. At time step t (day), when BPH population density is high (>10000 individuals/m^2) or rice growth stage is at the beginning of harvesting (> 85 days), long winged adults in one rice field will follow wind direction and migrate to other rice fields [12]. Duration for dispersing takes 5-7 days.

Multi-compartment model theory is employed to update the number of BPHs in the invading process. The study in [12] showed that the number of male and female long winged adults can be formulated as follows:

$$FML = FML_{growing} + \sum FMLI - FMLO$$

$$ML = ML_{growing} + \sum MLI - MLO$$

-$FML_{growing}$ and $ML_{growing}$ are calculated from BPH growth model (table 5), these are number of female long winged adults and male long winged adults inside area.

-∑FMLI, ∑MLI: number of female and male long winged adults from other areas moving into.

Table 7. BPH invasion rules

Name	Label	Expression
MLO	Number of male long winged BPHs moving out	ML /dispersal factor
FMLO	Number of female long winged BPHs moving out	FML /dispersal factor
MLI	Number of male long winged BPHs from neighbour areas moving into	MLO from original area
FMLI	Number of female long winged BPHs from neighbour areas moving into	FMLO from original area

Invading rules of BPHs are presented in table 7. Because only long winged adults can disperse, number of BPHs moving into and out an area are known as number of male and female long winged adults.

4. MODELLING BROWN PLANT HOPPER, GIS MAP DATA, WEATHER FACTORS AS AGENTS

Agent-based system [1][6] separates complicated systems in real world into components or objects called agents and interactions between them. Agent-based modelling is commonly employed in research related to technology, society and environmental fields [13], this approach helps visualizing real world and adding behaviours of agents. GAMA [5] is one of simulation platforms that help us model and simulate agent-based models. GAMA provides GIS tools to build spatial environment for agents, status of agents and their behaviours can be explored during simulation, this makes GAMA like a realistic environment [2].

Main agents designed in this model are: district, commune, rice, ricefield, weather, egg, nymph, adult. Each agent has attributes and behaviours to interact each other. When a land use GIS map data is loaded into simulation environment, commune agent will be created automatically and has certain attributes: code, name, area, coordinates and set of ricefield agent's ID. Each district agent knows which commune agents it includes. At each simulation step, each commune agent automatically update number of nymphs, adults, invading adults and BPH population density. Fig.1 describes a declaration of commune agent in GAML language on GAMA platform:

```
<species name="commune" skills="situated, visible">
<var type="string" name="ID_commune" />
<var type="string" name="name_commune" />
<var type="string" name="ID_province" />
<var type="string" name="ID_district" />
<var type="rgb" name="color" init="rgb 'white' " />
<var name="bphDensity" type="float" init="0"/>
<var name="bphAdultNums" type="float" init="0"/>
<var name="bphNymphNums" type="float" init="0"/>
………………
</species>
```

Figure 1. Commune agent is declared in GAML

A group of BPH adults include attributes (Fig.2) such as number of BPH adults, age, number of female and male long winged adults, number of female and male short winged adults, etc.

```
<species name="bphAdult" skills="moving, situated, visible">
<var name="districtObject" type="district"/>
<var name="nums" type="float" init="0"/>
<var name="age" type="int" init="0"/>
<var name="MLNums" type="int" init="0"/>
<var name="FMLNums" type="int" init="0"/>
<var name="MSNums" type="int" init="0"/>
<var name="FMSNums" type="int" init="0"/>
………………
</species>
```

Figure 2. A definition of BPH adult agent by GAML

The model is simulated in one cropping season (about 90 days). In each step, status of agents will be updated by rules in section 3. Fig.3 present simulation algorithm for the model:

```
input:
    1. Gis map data at administrative levels: district,
       commune;
    2. Gis map landuse data at levels: district, commune,
       ricefield;
    3. weather data from .csv files: temperature, humidity,
       rainfall, wind direction, wind speed;
    4. model parameters: number of simulation days,
       mortality rate of brown plant hoppers per day,
       colors to display levels of BPH density;
    5. light traps data from .csv file for validation purpose;

output: a 2-D chart describes BPH density results from
simulation steps and light traps BPH density data. A land use
map shows levels of BPH density at rice fields. A
administrative map shows BPH dispersal trends between
districts during simulation.

create agents: district, commune, rice, ricefield, weather, egg,
nymph, adult from inputs of the model. Initial statuses of
agents are setup from input data of the first day of making
rice crop;
foreach time_step from 1 to number_of_simulation_days do
    get weather data of current day;
    foreach agent is in [rice] do
        update rice growth stage;
    foreach agent is in [egg,nymph,adult] do
        get rice growth stage;
        update life span;
    foreach agent is in [ricefield] do
        update number of eggs, nymphs, adults;
        update BPH density of ricefield;
        if (BPH_density > 10000)
           or (rice_growth_stage >85) then
            get wind direction and speed from weather data;
            find set of potential rice fields that brown plant
                hoppers coud invade to;
            proceed invasion process and update BPH density
                at rice fields invaded;
    foreach agent is in [commune] do
        update statistically number of eggs, nymphs, adults
            from rice fields in commune;
        update BPH density of commune;
    foreach agent is in [district] do
        update statistically number of eggs, nymphs, adults
            from communes in district;
        update BPH density of district;
```

Figure 3. Simulation algorithm for BPH invasion

5. Experiment

5.1 Data used

An Giang, *Dong Thap*, *Tra Vinh*, *Soc Trang* are provinces in the Mekong Delta region that have typically heavy BPH infection in recent years. Because *Dong Thap* is a source of dispersing BPHs, experiments are carried out on communes in this province. For convenience in reading the paper, names of provinces, districts and communes are given in italic format.

The model uses GIS land use map data with basic attributes of province name, district name, commune name, commune area, rice crop, commune type and coordinates. Monthly data on temperature, humidity, wind direction and speed in 2009 are stored in .csv files and attributes at columns such as province code, district code, commune code, January, February, ..., December. The first row contains names of attributes and the next rows store monthly data.

Initial state of the model is set up by using observed data of BPH density at commune scale and the data is provided by Plant protection department in *Dong Thap* province. Light traps data are stored in .csv files for validation purposes.

BPH population size of one district is calculated from averaging BPH population sizes of communes that belong to that district. The simulation results will be compared with light traps data at district scale.

5.2 Experiment 1: rice crop in summer-autumn season

The starting date for simulation is 1st, July, 2009. Farmers begin summer-autumn rice crop at this time. The number of simulation steps is 90 days because the rice crop would be finished about 3 months. Wind direction is headed south-west at a speed of 12 km/h and the values of wind factor are kept fixed during simulation. Temperature and humidity factors have value of 24^0C-28^0C and 84%-86%, respectively and these values are read from input files. BPH mortality rate in this scenario is 3,5%. BPH population size and rice growth stages of communes are setup from table 8:

Table 8. Initial status of BPH population size and rice stages in communes

District	Commune	Rice stages (days)	Adult	Nymph	Egg
Tan Hong	Tan Thanh A	82	8000	300	
	Tan Thanh B	5	700	300	100
Hong Ngu	Thuong Thoi Hau A	10	200	200	

Real BPH infection situation in communes is shown in Fig.4. When starting the summer-autumn rice crop, *Tan Thanh A* commune in *Tan Hong* district is infected with high density (in orange color) and rice is in the harvesting stage. *Tan Thanh B* commune is lightly infected, whereas *Thuong Thoi Hau A* commune in *Hong Ngu* district is only infected with low BPH density (in white color).

The results simulation after 30 steps (Fig.5), with temperature $26,5^0$C and humidity approximately 84%, group of BPHs in communes (✱) in *Tan Hong* district followed the south-west wind direction to invade communes in *Hong Ngu* (◆), *Tam Nong* (●) and *Thanh Binh* (■) districts. Moreover, *Thuong Thoi Hau A* commune in this case is in orange color (high density) and is also a dispersal source to other regions.

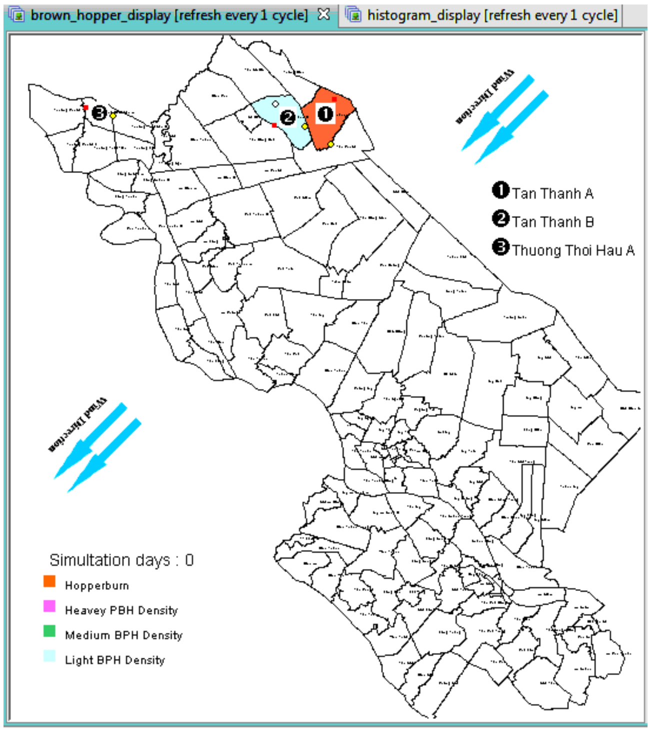

Figure 4. Initial status of experiment 1

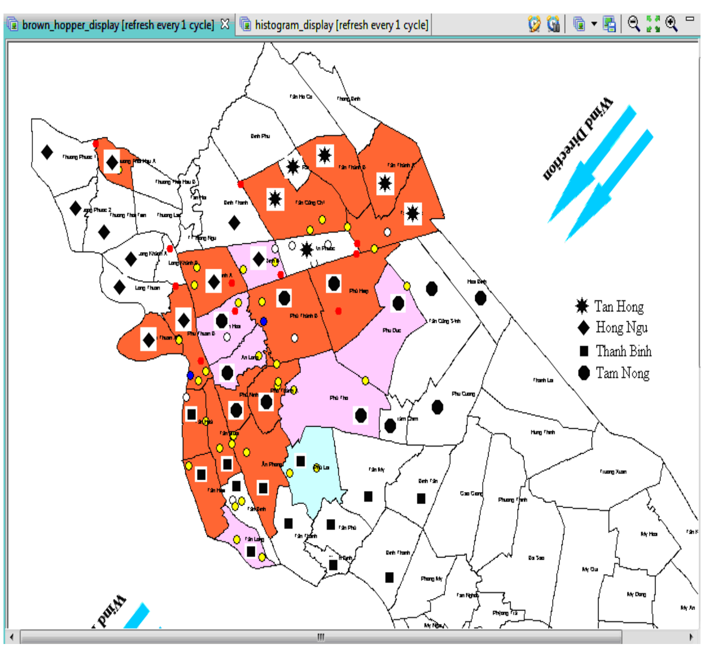

Figure 5. Simulation results after 30 steps

The results of BPH density (Fig.6) after simulation (90 steps) are validated by light traps data of four districts: *Hong Ngu*, *Tam Nong*, *Thanh Binh*, *Tan Hong* on July (Fig.7), August (Fig.8) and September (Fig.9).

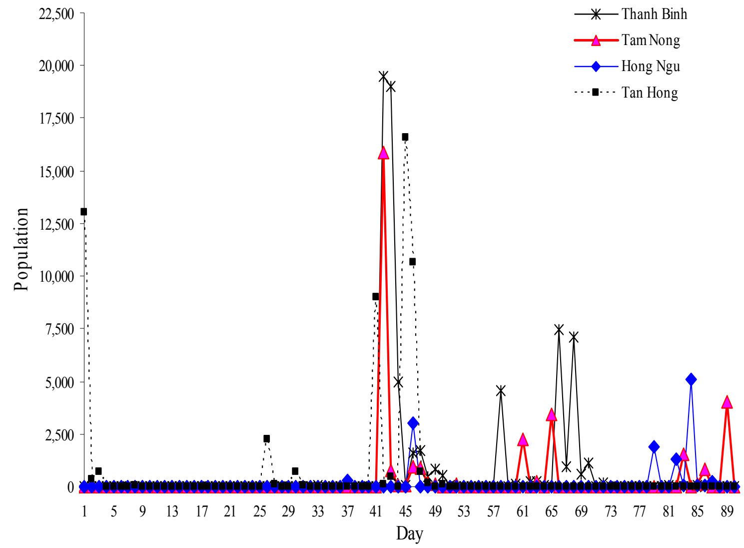

Figure 6. BPH population sizes of Tan Hong, Hong Ngu, Tam Nong, Thanh Binh after simulation

In the first three days of the dispersing phase, BPH population peaked on the third day (Fig.6). In the chart of light traps of *Tan Hong* district on July (Fig.7) BPHs disperse during the first 6 days with population size of peaking on the fifth day. Thus the first dispersing phase in simulation and real situation is different slightly about 3 days and both first dispersing phases appeared in the first week of July.

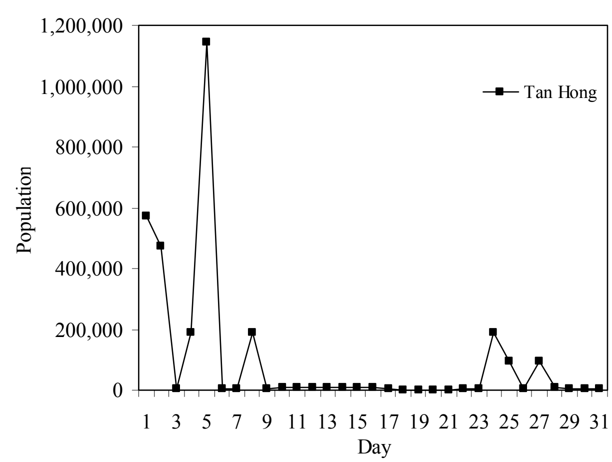

Figure 7. Light traps data at Tan Hong district (July, 2009)

In the second dispersing phase in simulation model, the heavy infection stage appears in *Thanh Binh* and *Tam Nong* districts in the second week of August (Fig.6) and in comparison with light traps data (Fig.8), peak population sizes at both districts appeared in the first week of August.

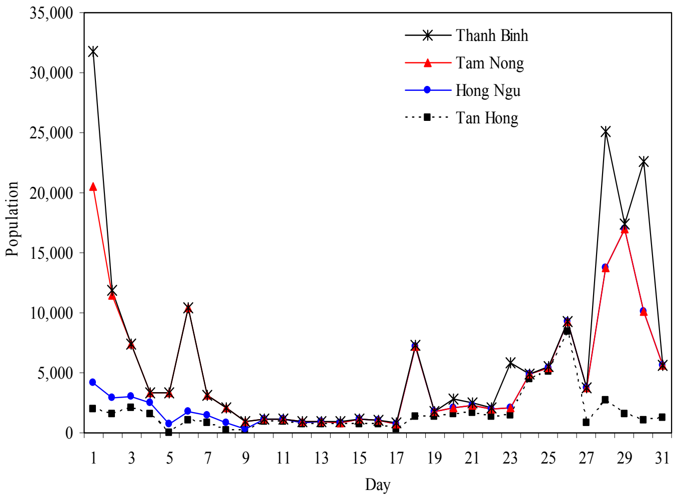

Figure 8. Light traps data of Tan Hong, Hong Ngu, Tam Nong, Thanh Binh (August, 2009)

In Fig.6, groups of BPHs dispersed from districts: *Tan Hong*, *Hong Ngu*, *Tam Nong* to *Thanh Binh* district during the first week. The results is suited with light traps data (Fig.9) that has the highest peak population size in *Thanh Binh* district.

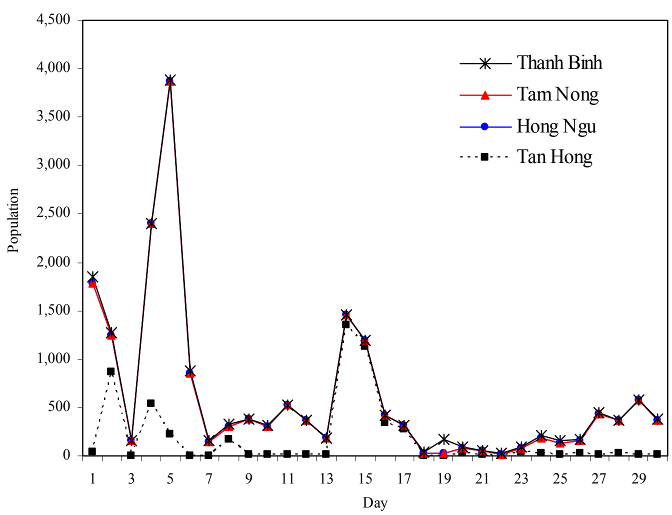

Figure 9. Light traps data of Tan Hong, Hong Ngu, Tam Nong, Thanh Binh (September, 2009)

BPH density values resulting from simulation, the model fitted approximatly 80% in comparison with the light traps data by using peak population size data in areas. The model predicts more accurately the duration when high BPH density occurs and the peak population size in the areas, e.g. when we observe charts on July and August of *Tan Hong*, *Hong Ngu*, *Tam Nong* and *Thanh Binh* (Fig.7, 8), groups of BPHs start invading about 5 days from *Tan Hong* district, then after 30 days BPHs appear in neighbour regions including *Tam Nong*, *Thanh Binh* districts and the highest BPH population size is in *Thanh Binh* district.

5.3 Experiment 2: synchronous rice transplanting policy

This experiment tries to understand affects of the policy that farmers simultaneously do rice transplanting at rice fields in communes in *Dong Thap* province to BPH growing and invading processes.

Initial status of experiment is on January 1, 2009 and farmers is making the winter-spring rice crop. Because farmers start rice transplanting at different time, almost communes is on the 20th-30th day rice growth stage, some communes started too early and is on the 50th-60th day rice growth stage and therefore these communes are infected by group of BPHs following the south-west wind direction from communes haversting the autumn-winter rice crop (from october).

Wind factor has a speed of 12 km/h and heads of north-east direction. Temperature is 23^0C-24^0C and humidity is 85%-87%. BPH mortality rate in this scenario is 3,5%. BPH population sizes are setup in table 9, rice growth stages at communes are supposed to be the same and are on the 80th day:

Table 9. Initial status of BPH population size and rice stages in communes

District	Commune	Rice stages	Adult	Nymph	Egg
Cao Lanh	My Hiep	80	2500	8000	
	My Long	80	600	900	
	My Tho	80	200	800	
	Binh Hanh Trung	80	200	800	
Lap Vo	Vinh Thanh	80	200	500	
Lai Vung	Long Hau	80	800		
TP.Cao Lanh	My Tra	80	80		
	My Tan	80	50		

Initial status of experiment 2 is showed in Fig.10.

❶ My Hiep
❷ My Long
❸ My Tho
❹ Binh Hanh Trung
❺ Vinh Thanh
❻ Long Hau
❼ My Tra
❽ My Tan

After 15 simulation steps, BPHs developed slowly in communes because rice crop has just begun the blossom stage.BPH groups are dispersed by wind to other areas to find food (Fig. 11):

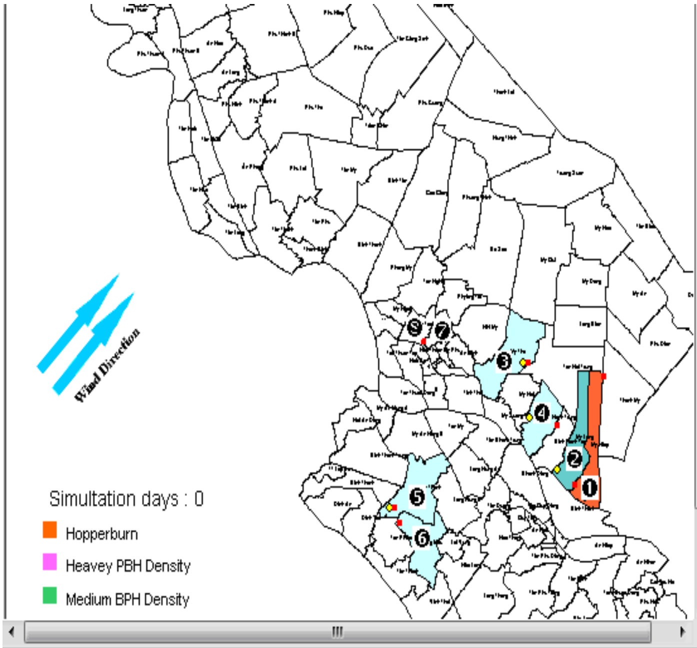

Figure 10. Intial status of experiment 2

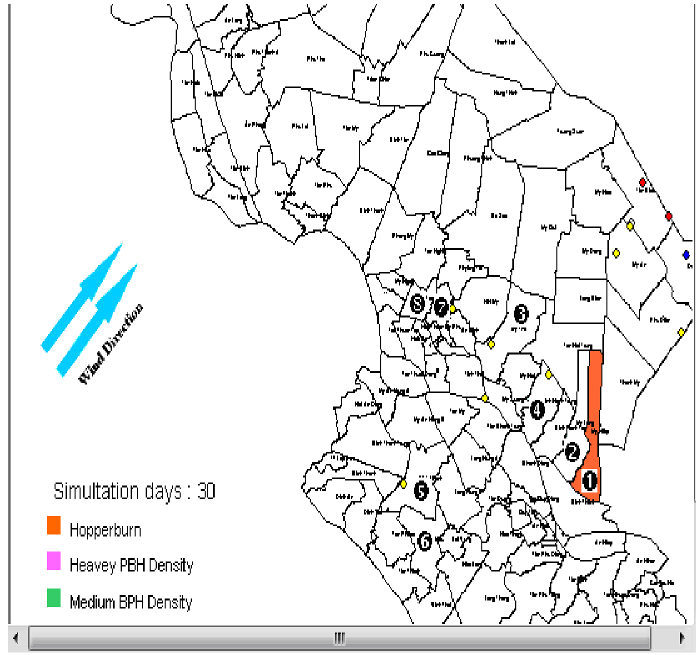

Figure 12. The simulation results in 30th step

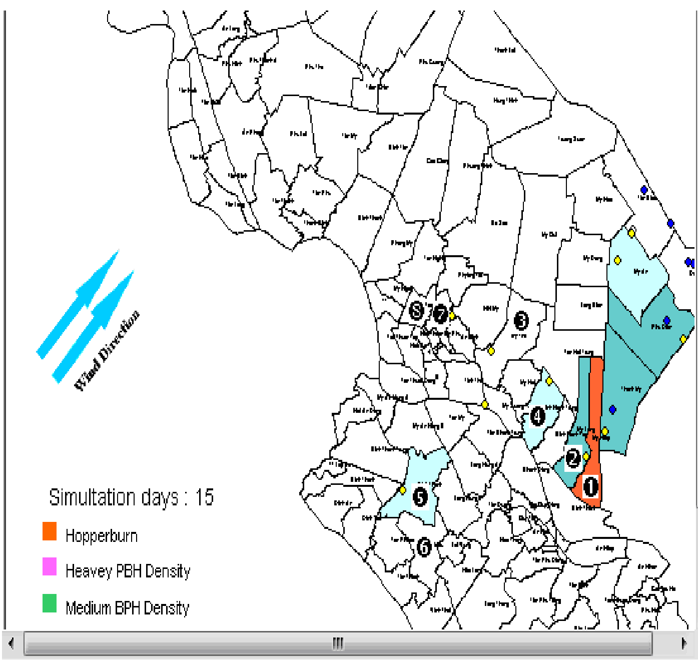

Figure 11. The simulation results in 15th step

Fig. 12 presents results at the end of rice crops, BPH densities in the communes are very low because almost rice crops at this time are in ripening stage.

Above results proved that the policy of synchronous rice transplanting in the communes leads to BPHs cannot find food in the target areas when they move into. Thus this is a way could help farmers avoid BPHs invasion.

6. CONCLUSION

This paper designed a growth and invasion model of Brown plant hoppers at commune scale and the model used GIS land use map data and captured environmental entities in the real world into agent-based system. Users can try different scenarios by changing values of input parmameters and understand directly the BPHs growth and invading processes in a region on GIS map. Equations of BPHs population density are integrated with weather rules of temperature, humidity, rainfall to build this model. In the next steps, this model can be improved by adding other factors such as rice variety, fertilizer, air pressure so that stakeholders can choose appropriate farming policies to help farmers improve rice products. Agent-based modelling concepts and programming on GAMA platform have proved their usefulness in visualizing ecology processes in general and BPHs invading process during rice crops in the Mekong Delta in particular. Decision makers could base on results of simulation to make prediction and prevent plans of BPH invasions, these help farmers in improving rice crops.

7. ACKNOWLEDGMENTS

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