Efficiency of Mycoinsecticides Controlling Pest Populations of the Brown Planthopper in Rice. A Simulation Model

Dieter H. Knösel
Institute of Applied Botany
University of Hamburg

Claus Peter Ortlieb
Institute of Applied Mathematics
University of Hamburg

CEC Research Contract TS3* - CT92-0018
February 1996

1 Introduction: Biological control of insect pests of rice

Rice (*Oryza sativa* L.) is one of the most important cultivated plants of tropics and subtropics. Next to wheat and maize, it is in the third place of global cereals production. In suitable regions it is tilled already for long times by sowing directly or by transplanting, and represents the main food there.

Hopperburn of Rice, Java Indonesia January 1994

Many diseases and pests are impairing the crop, total losses occur many times. A cicada species, the Brown Planthopper *Nilaparvata lugens* STAL., is of particular importance, because it is responsible for the transmission of rice vi-russes which are called *grassy stunt*, *ragged stunt*, and *wilted stunt* viroses. Infected rice plants are yellowing and dieing away, called *hopperburn*. Ordinarily, the rice fields are invaded by long-winged adults. 7 - 10 days after oviposition, they are developing from eggs into nymphs which are passing through five stages during 13 - 15 days. After that, the short-winged cicada is prevalent until rice bloom. The females are hidden among tillers at the base of the hills. At the beginning of the harvest the long-winged migrating adult is developing.

The Rice Ragged Stunt Virus (RRSV) has been studied exhaustively, its spreading included. It is adjoined the subgroup 3 of Phyto-Reovirusses. The replication within the Brown Planthopper is beginning three hours after acquisition by sap sukking. Having passed through a latent period of ten days, the cicadas are transmitting the virus lifelong.

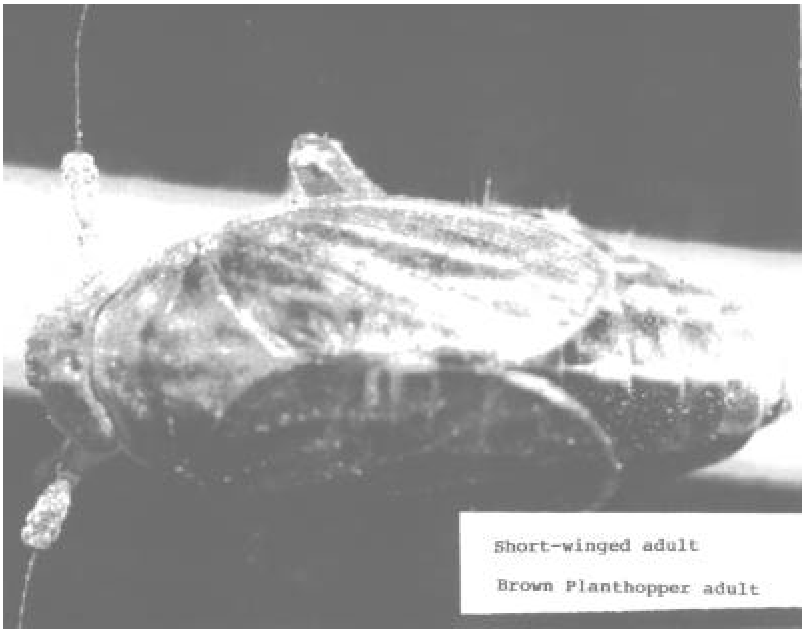
Hopperburn of Rice
Brown Planthopper transmits Rice Ragged Stunt Virus.
Adults are found among tillers at the base of the hills.

Specially proved insecticides are applied for the purpose of controlling the Brown Planthopper. It cannot be excluded that residues of the additives being left in the rice grains. But this fact is not determining the aspired reduction of applying common insecticides, rather there is a *pesticide-syndrom*: Any application of insecticides on a large scale is affecting antagonists too causing later increasing of the Planthopper populations. The most important antagonist of *Nilparvata* is the wolf spider *Lycosa pseudoannulata* BOES et STR.

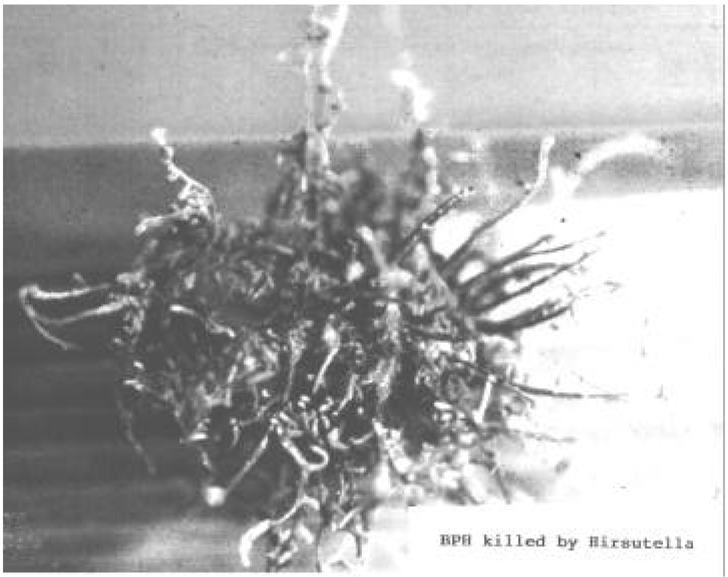
As a consequence predators, parasitoids, and entomopathogenic fungi are possible candidates for biological control of the virus-transmitting cicadas, provided that the fungi do not infect the present predators. Fungus species of such a kind are known since some time. But only in the last decades, first attempts are to be recognized in developing mycoinsecticides and utilizing them for the purposes of integrated plant protection strategies. SOPER / WARD 1985 and SOPER 1982 are treating relevant aspects exhaustively. Certain problems have been identified concerning the mass production of mycelia and spores, the formulation, storage, transport of preparations without loss of virulence, the application form, and particularly the efficiency compared to that of chemical insecticides, finally the compatibility with fungicides which may possibly being applied against mycoses.

About twenty preparations have been brought onto the market in last years. They are applied against certain pest insects in North America, Brazil, Australia, and European countries.Apart from application in laboratories and greenhouses, there are no reports of being comprehensively succesfull in largely sized plant cultivation. This fact give rise to examinating essential interdependencies and requirements.Within the framework of the project **Integrated Strategies for the Biological Control of Major Insect Pests of Rice in South East Asia** of the European Communities, Science and Technology for Development, it has been possible

- to record known facts in a database,
- to obtain new results by biological experiments,
- on this basis, to examine with the aid of a mathematical model whether insect pests on rice are to be controlled in principle by applications of mycoinsecticides,
- to specify the requirements being necessary for that.



The model is referring to the development of the Brown Planthopper population, *Nilparvata lugens* STAL, under the influence of mycoinsecticid being formulated by the spores of the fungus species *Hirsutella citriformis* SPEARE. For the purpose of biological experiments rice cicadas have been collected at Java, Indonesia, and transfered to Hamburg being kept there in cultures on suitable rice plants. Strains of the pathogenic fungus had been isolated from naturally infected cicadas originating from Indonesia, Philippines, and Sri Lanka. By laboratory and greenhouse experiments the culture conditions for sufficiently high spore production has been acquired, and the form of application has been developed. The mortality effect has been determined in test series compared to already approved entomopathogenic fungus species.


BPH killed by Hirsutella

The model being described in the following comprehends the densities of the Brown Planthopper and the manipulated pathogenic fungus as stock sizes, but not the densities of natural enemies. They are rather been held constant as external model parameters. The model may be seen as some first steps to a realistic computer simulation model of pest control by mycoinsecticides.

The model has been presented within the scope of the lecture „Efficiency of Mycoinsecticides controlling Pest Populations of the Brown Planthopper in Rice in context with Mathematical Modelling“ given on the international workshop **Sustainable Insect Pest Management in Tropical Rice**, December 5 - 7, 1995 in Bogor, Indonesia.

2 The linear BPH submodel

2.1 Modelling assumptions

2.1.1 BPH's course of life

The Brown Planthopper *Nilparvata lugens* STAL spends

- 10 days of its life as *egg*,
- 15 days as *nymph*,
- 30 days as adult *cicada*.

Considering a cohort,

- 30% of the eggs attain the nymph stage,
- 40% of the nymphs attain the cicada stage,
- thus, 12% of the eggs attain the adult stage.

In the mean

- each female oviposits 15 eggs per day,
- thus, the number of eggs ovipositted per day is 7.5 times the number of adult cicadas present.

2.1.2 Predation and mycosis infection

The growth of the BPH population is affected by another two causes of deaths. One of them, called *predation*, is working immediately. The other one is the mycosis *infection* working with a time lag of three days. For predation only its immediate effect is important with respect to the BPH's population dynamic. So you may subsume under it becoming a prey of antagonists (spiders, *Lycosa*) as well as pest control by chemical insecticides. It is assumed that

- this two causes of death concern the adult individuals only,
- three days are passing from mycosis infection until the death of the infected individual,
- the rate of oviposition (15 eggs per day and female adult cicada) does not change during this time.

2.1.3 Scarcity of food

It is assumed in the following that

- the possible scarcity of food (rice plants) does not mean any limit of growth of the BPH population.

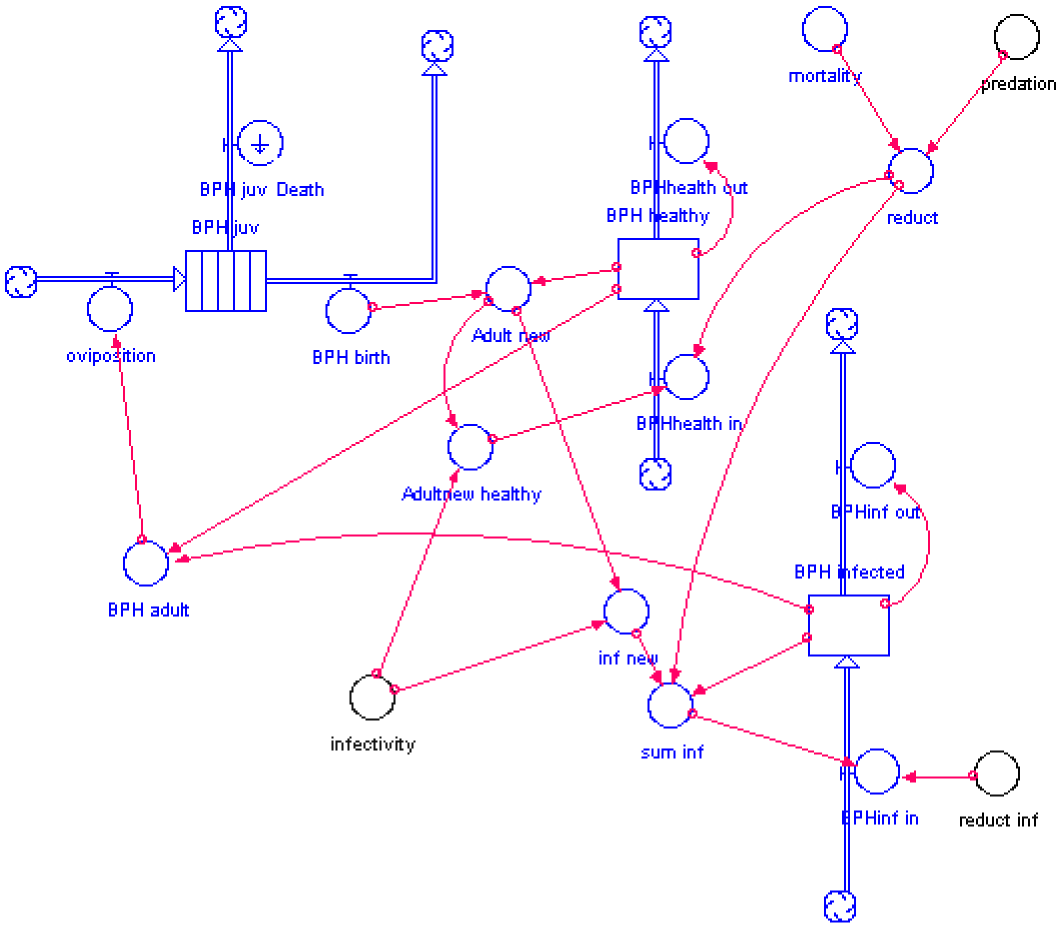
Of course, this assumption is not realistic. It is acceptable, however, with respect to the purpose of the the model: Any population density of *two individuals ore more per tiller* give rise to a break down of the system. The assumption is that the population growth is not impaired by the scarcity of food below this threshold. It is examined in the following, whether or not, how far and in which way the BPH population density may be kept below it.

2.2 The Stella model

The Stella model is conceived with a time step of one day to make simulation runs fast. Great time steps like this contain the possibility that stock sizes get negative. We are deviating from Stella's general philosophy to avoid this undesirable effect, and describe decreases by multiplicative factors less than 1 instead of subtractions as usual. To make the concept clear by example: Let y(t) the number of healthy cicadas per tiller at time t, let c the part of cicadas killed by predation per day, and p the part of healthy cicadas getting infected per day, then

- $y(t+1) = y(t) - c\,y(t) - p\,y(t)$ by Stella's common philosophy. This value gets negative if
  $c + p > 1$,
- $y(t+1) = (1-c)\,(1-p)\,y(t)$ by our concept. This value cannot get negative.

2.2.1 Stella diagram



2.2.2 Model variables and equations

name	meaning	value
BPH juv	number of juvenile BPH (eggs + nymphs) per tiller	conveyor, transition time = 25
BPH healthy	number of healthy adult BPH per tiller	
BPH infected	number of infected adult BPH per tiller	
BPH adult	number of adult BPH per tiller	BPH healthy + BPH infected
infectivity	part of healthy BPH getting infected per day	
mortality	part of BPH deceasing by age per day	0.035
predation	part of BPH being killed per day	
reduct	factor of reduction by mortality and predation	(1 - mortality) (1 - predation)
reduct inf	factor of reduction of infected BPH per day	0.6
oviposition	number of eggs laid per tiller and day	7.5 * BPH adult
BPH birth	number of nymphs attaining the adult stage per day	0.12 * BPH juv (last generation)
Adult new	number of yesterday's healthy adults per tiller	BPH birth + BPH healthy
Adultnew healthy	number of yesterday's healthy adults keeping healthy per tiller	(1 - infectivity) * Adult_new
inf new	number of newly infected adults per tiller and day	infectivity * Adult new
sum inf	sum of infected adults per tiller	reduct * (BPH infected + inf new)
BPHhealth in	number of healthy adults staying alive per tiller	reduct * Adultnew healthy
BPHinf in	number of infected adults staying alive per tiller	reduct inf * sum inf

The BPH population density (number of individuals per tiller) refers to the number of tillers in a medium rice-field. The model neglects the increase of the tillers' number and size. This is possible as long as one neglects the effect of the rice stock on the BPH population (see 2.1.3).

2.3 Mathematical formulation and analysis

2.3.1 Linear discrete dynamical system

Let us denote in shorter terms than in the Stella model

- $x_i(t)\ (i = 1,\dots,25)$ the number per tiller of i days old juvenile BPH,
- $y(t)$ the number per tiller of adult healthy BPH,
- $z(t)$ the number per tiller of adult infected BPH.

The parameters

$$c = \text{predation} \ , \ p = \text{infectivity}$$

have no prescribed values until now. The population densities result from that of the previous day by the equations

$$\begin{aligned} &x_1' = 7.5(y+z) \\ &x_i' = x_{i-1}\ (i = 2,\dots,25) \\ &y' = 0.965(1-c)(1-p)(0.12\,x_{25} + y) \\ &z' = 0.579(1-c)(z + p(0.12\,x_{25} + y)) \end{aligned}$$

where 0.965 = 1 - mortality, and 0.579 = 0.6 * 0.965 = reduct inf * (1 - mortality).

2.3.2 Mathematical analysis

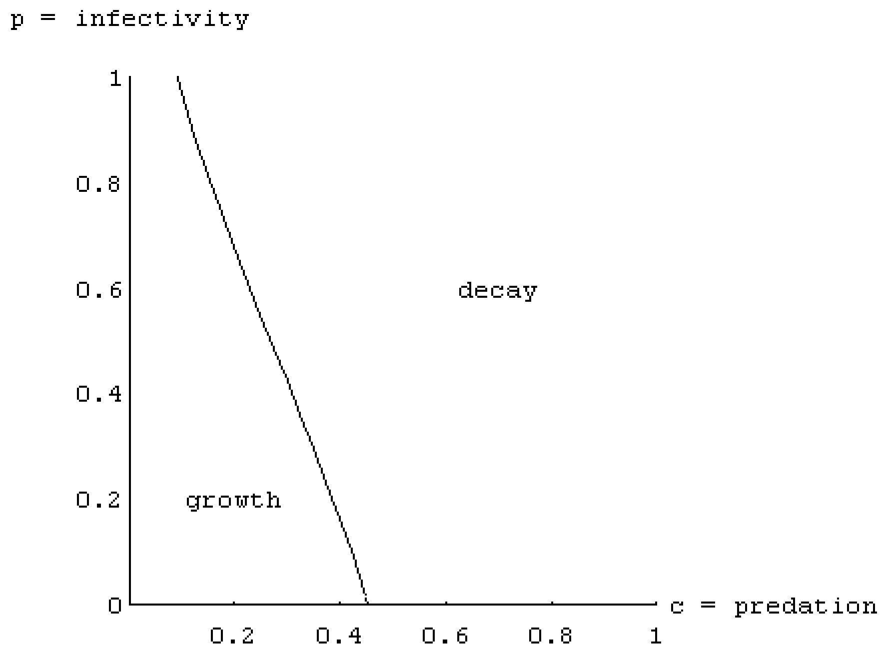
The equations describe a homogeneous linear discrete dynamical system with nonnegative, irreducible system matrix A. The absolutely greatest eigenvalue of A is real and positive (Theorem of Perron-Frobenius, see e. g. LUENBERGER 1979). It depends on the sign of the determinant

$$\det(I - A)$$

with the identity matrix I, whether the Perron-Frobenius eigenvalue is less or greater than 1 (decay to zero or unbounded growth, see e. g. LUENBERGER 1979, SANDEFUR 1990). This term is a function of c and p which is easy to evaluate (using *Mathematica* e. g.). For any given c there is a critical value

$$p_c = \frac{0.350904 - 0.289307c - 1.0616c^2}{0.250804 + 0.810793c - 1.0616c^2}$$

such that the Perron-Frobenius eigenvalue is less than 1 if and only if $p > p_c$.



We have $p_c = 1$ for $c = 0.0909917$, $p_c = 0$ for $c = 0.454595$, while p_c is strictly decreasing for $0.0909917 < c < 0.454595$.

2.4 Biological implications

It cannot be expected that the exponential growth of the BPH population is stopped by mycosis infection without an additional cause of death like predation. The reason is that infected individuals are surviving three days without loss of their reproductive power. Each female is ovipositting $0.12 * 7.5 = 0.9$ female eggs per day which attain the reproductive stage, that is 2.7 in three days sufficing for exponential growing even of a fully infected population. This result depends on the modelling assumption that juvenile individuals (eggs und nymphs) cannot be infected, and becomes wrong without this assumption.

Stopping the growth of BPH population by mycosis infection is possible only if the loss by predation amounts 10% per day of the adult population at least.

Predation of more than 45% per day of the adult population causes a break down of the BPH population even without mycosis infection.

Any amount of loss by predation between 10% and 45% per day is connected with a critical rate of infection beyond which the BPH population breaks down.

Without predation, even a fully infected BPH population is exponentially growing, but the growth is considerably slower than that of an healthy population. Slowing down by mycosis infection might be sufficient for protection of the rice plants even in this situation, as later simulation experiments will show.

3 The BPH-Hirsutella model

3.1 Modelling assumptions

The Hirsutella population is coming into play. Its densitiy is given not per tiller but per area. The area unit is 1 m^2 carrying about 1000 tillers in the mean.

3.1.1 Hirsutella's course of life

The Hirsutella spores enter the system on two different ways:

- Each cicada died by infection produces 100 000 new Hirsutella spores. Thus, one cicada per tiller died by infection is increasing the Hirsutella density by 100 000 000 spores per m^2.
- Mycoinsecticides are spread; it is assumed that each application is increasing the Hirsutella density by 500 000 000 spores per m^2.
- The spores are assumed to survive 40 days in the mean, that is
- 2.5% of the Hirsutella spores are leaving the system per day.

3.1.2 Hirsutella density and infection rate

The infection rate p is a function $p = p(u)$ of the Hirsutella density u . It cannot be quantified by laboratory experiments. We are assuming a monotone function with the properties

$$p(0) = 0,\ p'(u) > 0 \text{ and } p(u) \to 1 \text{ for } u \to \infty \ .$$

- Supposing the random infection of a cicada by a spore as independent from the infection by another, we get the approach

$$p(u) = 1 - e^{-l\,u} \quad \text{with a constant } l > 0 \ .$$

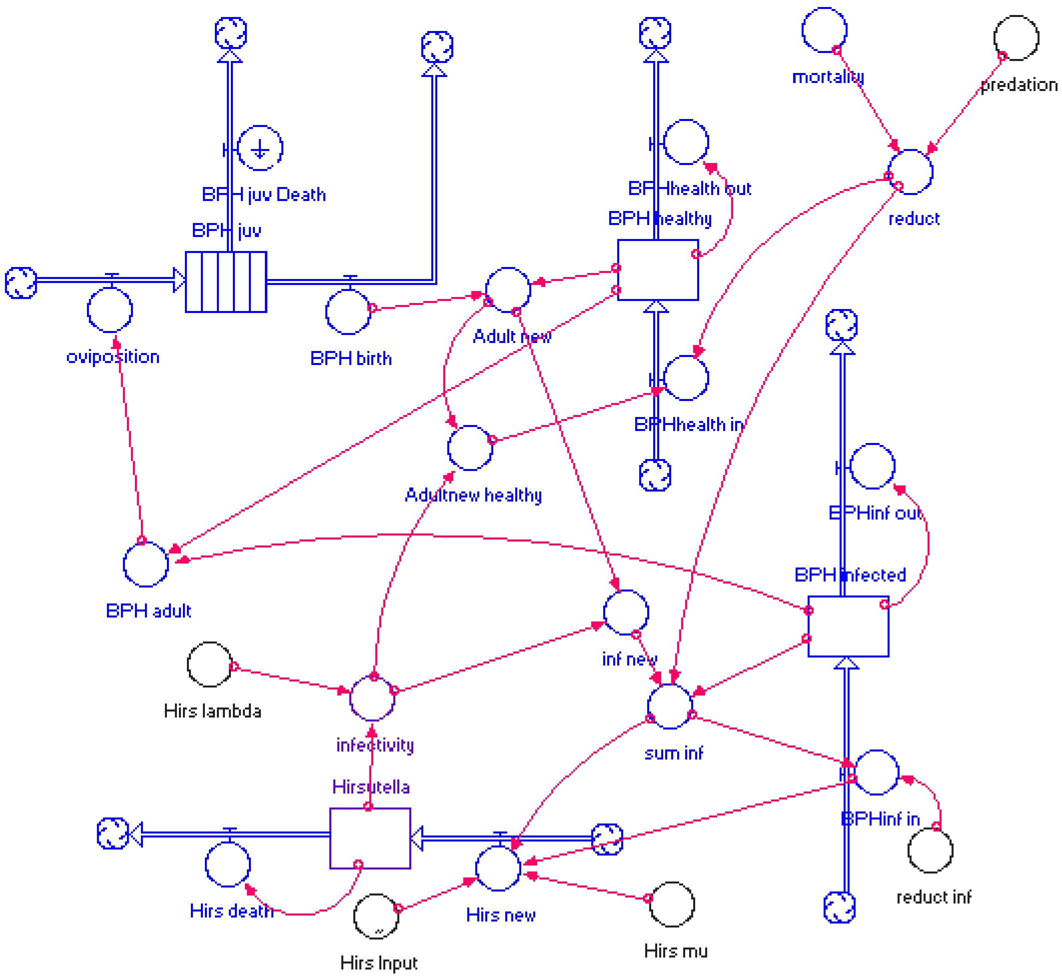
It is not clear, however, which value for the constant l is to be choiced. l describes the efficiency of the Hirsutella spores in infecting the cicadas: The greater l , the less spores are necessary to cause a given infection rate.

3.2 The Stella model

3.2.1 Model variables and equations

name	meaning	value
Hirsutella	number of Hirsutella spores per m^2	
Hirs death	number of spores dieing per day	0.025 * Hirsutella
Hirs input	number of spores spread from outside	
Hirs mu	sporulation factor	100 000 000
Hirs new	number of new spores per day	Hirs mu * (sum inf - BPHinf in) + Hirs input
Hirs lambda	efficiency of spores	
infectivity	part of healthy BPH getting infected per day	1 - Exp(- Hirs lambda * Hirsutella)

3.2.2 Stella diagram



3.3 Mathematical formulation and analysis

3.3.1 Discrete dynamical system

The abbreviations

- $u(t)$: number of Hirsutella spores per m^2 at time t,

l = Hirs lambda , m = Hirs mu = 100 000 000 , k = Hirs input

lead to the discrete dynamical system completed by an equation for Hirsutella spores

$$x_1' = 7.5(y+z)$$
$$x_i' = x_{i-1} \ (i = 2,\ldots,25)$$
$$y' = 0.965(1-c)(1-p)(0.12\,x_{25}+y)$$
$$z' = 0.579\,(1-c)(z+p(0.12\,x_{25}+y))$$
$$u' = 0.975u + 0.386m\,(1-c)(z+p(0.12\,x_{25}+y)) + k \ ,$$

with $$p = p(u) = 1 - e^{-l\,u} \ .$$

3.3.2 Interior equilibrium

For 0.0909917 < c < 0.454595 and k = 0 there is exactly one stationary state with positive values of all stock variables, and $p(u) = p_c$ (see 2.3.2), thus

$$u = \frac{1}{l}\log\left(\frac{1}{1-p_c}\right).$$

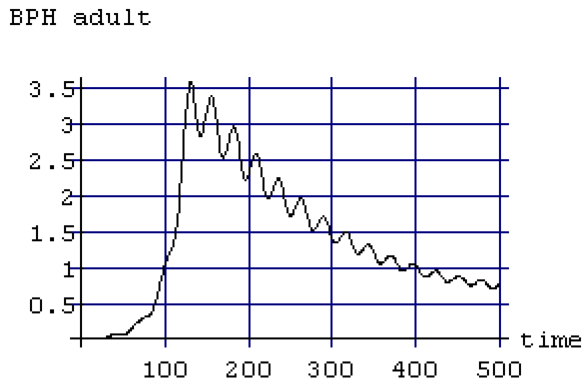
In the equilibrium point the linear BPH subsystem possesses the Perron-Frobenius eigenvalue 1 with a positive eigenvector, which is to be choiced such that

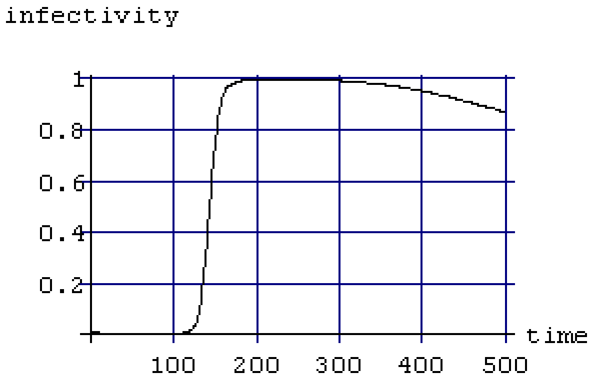
$$0.386m\,(1-c)(z+p_c(0.12\,x_{25}+y)) = 0.025u \ .$$

Numerical examples

c	l	p_0	y	z	u	stability
0.15	1 E-10	0.81375	1.22096	6.30249	1.68066 E+10	0.998443
0.15	1 E-9	0.81375	0.122096	0.630249	1.68066 E+9	0.998443
0.2	1 E-10	0.676328	1.81117	0.423009	1.12802 E+10	0.998781
0.2	1 E-9	0.676328	0.181117	0.211504	1.12802 E+9	0.998781
0.25	1 E-10	0.548175	2.31541	2.97922	7.9446 E+9	0.998955
0.25	1 E-9	0.548175	0.231541	0.297922	7.9446 E+8	0.998955
0.3	1 E-10	0.423008	2.78807	2.06223	5.49927 E+9	0.998956
0.3	1E-9	0.423008	0.278807	0.206223	5.49927 E+8	0.998956

The predation rate c determines the infection rate p in the equilibrium as well as the ratio of the stock variables whose absolute values depends linearly on $1/\lambda$. The last column is containing the absolute value of the absolutely greatest eigenvalue of the Jacobian in the equilibrium point which is independent of λ too. It is only somewhat less than 1 for all computed numerical examples, and resulting from a pair of conjugate complex eigenvalues. Therefore, we expect oscillations with small damping (see e. g. LUENBERGER 1979, SANDEFUR 1990).





The progress shown above (c = 0.15 , λ = 1 E-9) is typical of initial values at the beginning of the cultivation period, which are small compared to the equilibrium: The BPH population is growing during the whole cultivation period of 120 days; it tends to the equilibrium later on only, in an oscillating manner. Thus, the stationary point appears to be irrelevant with respect to the purpose of our model.

3.4 Simulation runs

Apart from the unknown parameter values

c = predation , λ = Hirs lambda

the initial values of the stock variables give rise to uncertainty. They are tuned in the following simulations to a maximal value of about two individuals per tiller obtained by the (non-controlled) adult BPH population during a cultivation period of 120 days. That is, in all simulations, the crop would be destroyed completely if no mycoinsecticides were spread.

We assume in an arbitrary manner with respect to the application of mycoinsecticides that a dose of

5 E+8 spores per m^2

is spread each of *three different days*.

The progress of the adult BPH population and, partially, of the infection rate is shown. Moreover, you see the population density's mean value over the whole cultivation period in the head of the BPH graph.

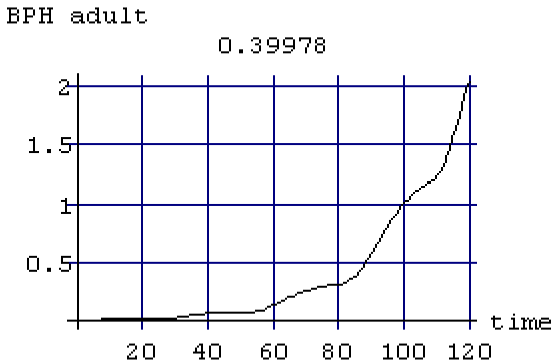
For better handling of graphics within text processing the graphs are produced with the aid of *Mathematica* instead of *Stella*. Of course, the results are not concerned of that.

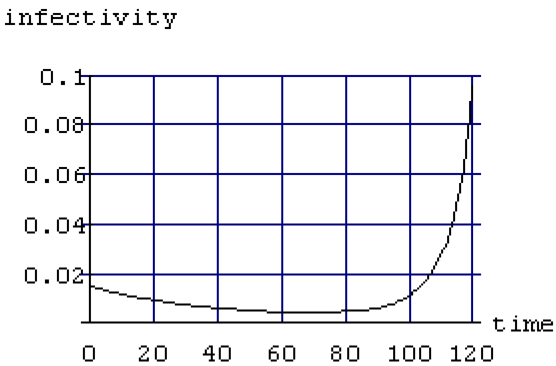
3.4.1 predation = 0.15 , Hirs lambda = 1.5 E-9

Initial values
BPH juv = 1 , BPH healthy = 0.002 , BPH infected = 0 , Hirsutella = 1 E+7

To begin with, we consider the case of no application of mycoinsecticides. The infection rate increases in the course of 120 days because the conditions for the genuine Hirsutella population get better as the BPH population is growing. But increasing comes too late and is too small, and the whole crop will be destroyed:

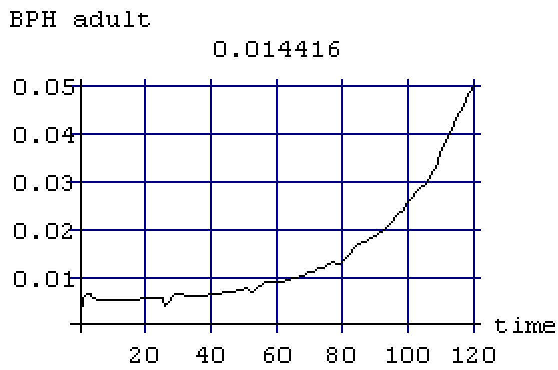
No application of mycoinsecticides

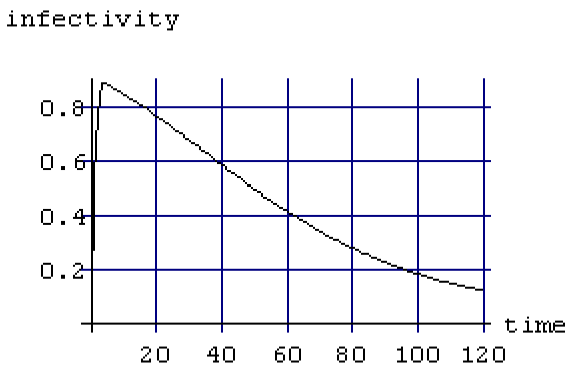




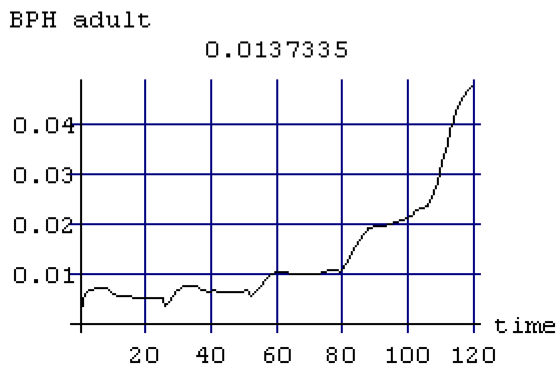
Computer experiments are documented in the following, which are different from another concerning the dates of application of the designated dose. Because of the 40 day life-span of the spores, every application of myco insecticides does not only increase the infection rate at the same day but for a longer period. For that reason, it is obvious to applicate at least the first dose as early as possible. We consider the BPH population density's mean value over the whole cultivation period of 120 days as a criterion for the efficiency of pest control. Then, the early application will be a good strategy indeed, as our experiments show. It is not optimal in any case, however, to spread the whole dose at the beginning. The reason is that the infection rate is a *nonlinear* function of the Hirsutella density: Every application do increase the Hirsutella density by the same size but the resulting increase of the infection rate is a strictly decreasing function of the current infection rate itself. It is not worth while increasing it on a high level because the effect becomes low in proportion to the expenditure.

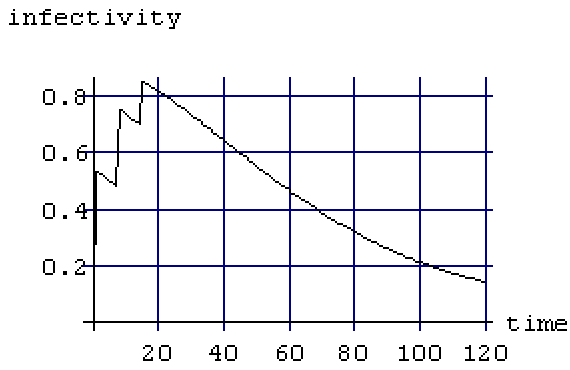
Application dates 0, 1, 2



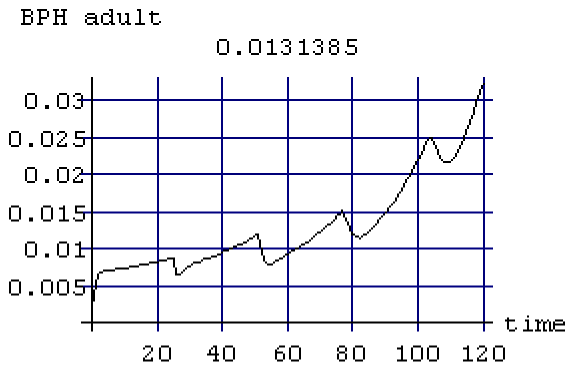


Application dates 0, 7, 14

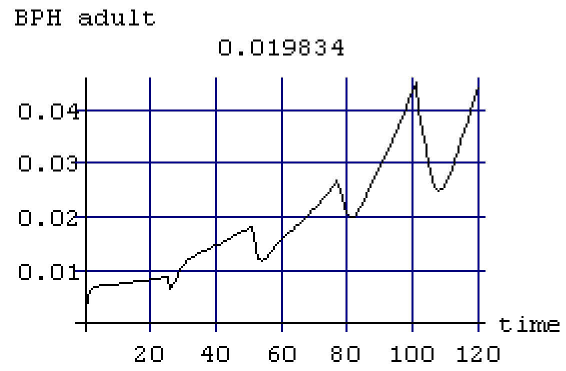




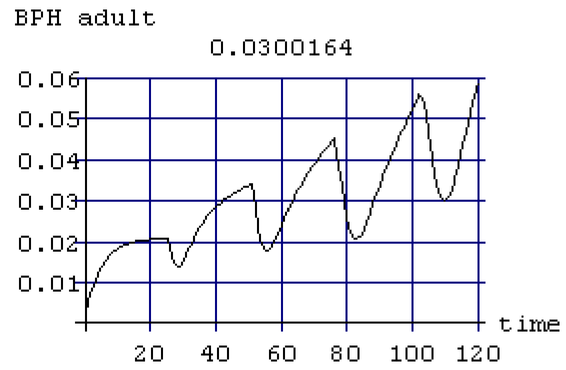
Application dates 0, 25, 50



Application dates 0, 50, 100



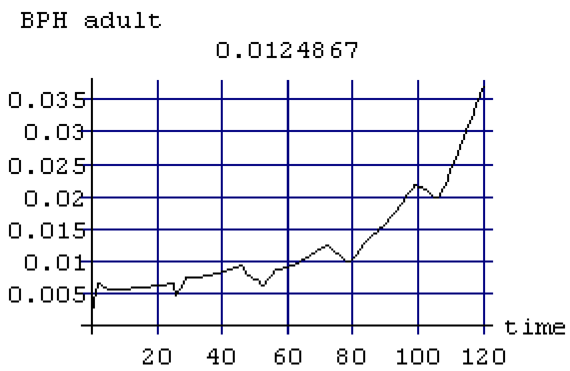
Application dates 25, 50, 75

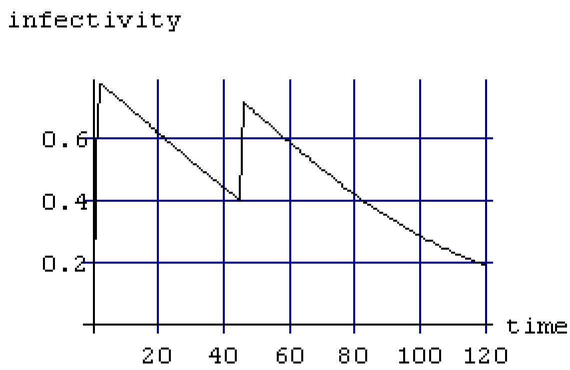


With the numerical values supposed in this series of experiments, the systematic attempt to minimize the mean value of the BPH population leads to the best strategy of application dates 0, 1 and 45. Two doses at the beginning causes a high level infection rate such that the next application is worth while only when it has decreased.

We have to warn against generalizing this solution. Other numerical initial and parameter values may lead to other optimal strategies.

Application dates 0, 1, 45





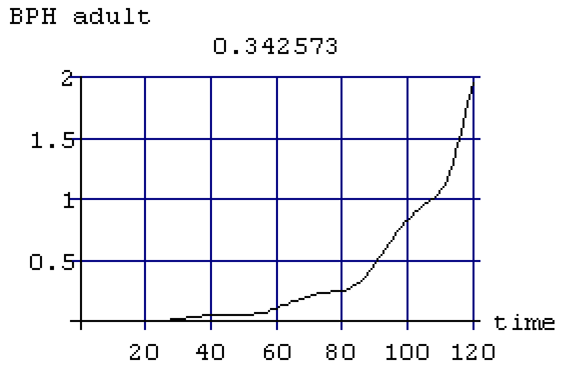
3.4.2

3.4.3 predation = 0.15 , Hirs lambda = 1.5 E-10

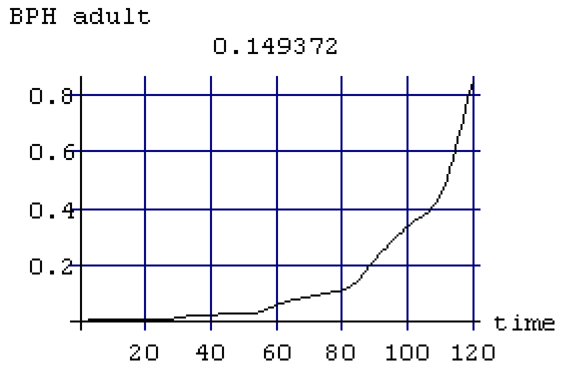
Initial values
BPH juv = 0.75 , BPH healthy = 0.002 , BPH infected = 0 , Hirsutella = 1 E+7

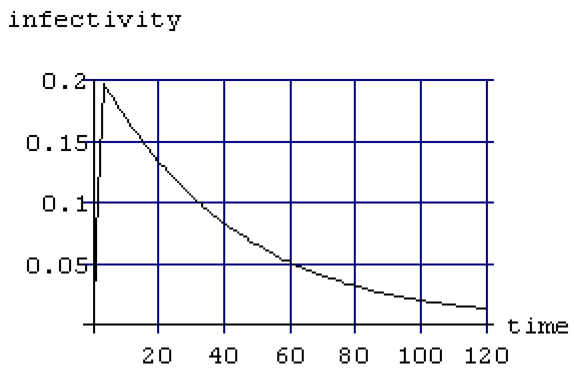
The factor λ determining the effect of the Hirsutella density on the infection rate has only a tenth of the value in the last series of experiments. The consequence is that a reduction of the BPH population is not possible in the same manner as before. The systematic attempt to minimize the mean value of the BPH population leads to the best strategy of applicating the whole dose at the beginning. The reason is that the first two applications bring infection to a value of about $p = 0.2$ only, where any additional application has an effect.

No application of mycoinsecticides



Application dates 0, 1, 2





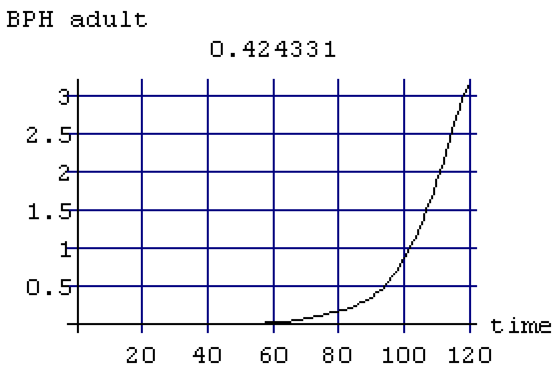
3.4.4 predation = 0 , Hirs lambda = 1.5 E-9

Initial values

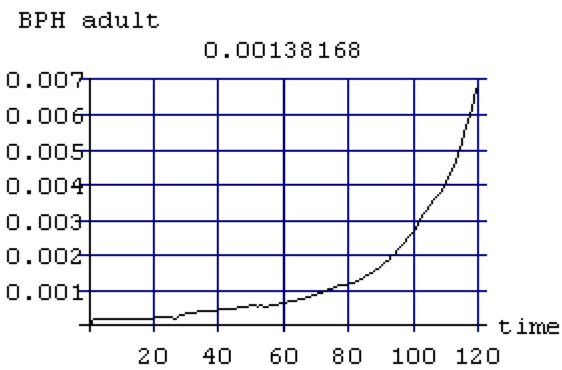
BPH juv = 0.025, BPH healthy = 0.00005, BPH infected = 0, Hirsutella = 1 E+7

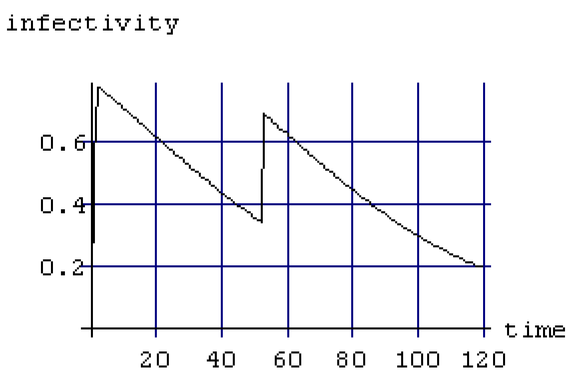
We are considering this time a situation with an exponential growth of the BPH population even if it is fully infected ($p = 1$) (see 2.3.2 und 2.4). To get a growth of the magnitude of the numerical examples before without application of myco-insecticides, we have to choice the initial values much less. Doing so, the application is essentially more effective than in the preceding series of experiments. The best strategy consists in the application dates 0, 1 und 52, similiar to that of 3.4.1, and on the same reason.

No application of mycoinsecticides



Application dates 0, 1, 52





3.5 Interpretation and valuation

3.5.1 Conclusions from the simulation runs

The numerical values of the simulation runs must not be overvalued since the parameter λ, determining the effect of the Hirsutella density on the infection rate, is unknown. Still some conclusions are possible:

- ♦ Pest control of BPH population by mycoinsecticides is possible in principle, though we will avoid any statement about the necessary dose.
- ♦ If a sufficient dose for pest control is available, it appears to be a good strategy
  - to spread at the beginning of the cultivation period with the purpose of a high level infection rate,
  - to spread once more only if the infection rate has decreased such that a significant increasing is possible by application of another dose.
- ♦ The notion of "high level" infection rate and "significant increasing" depends on the available total dose as well as on the applicable dose of one day.

3.5.2 Uncritical modelling assumptions

The modelling assumptions

- that infection and predation concern the adult individuals only,
- that the possible scarcity of food does not mean any limit for the BPH population's growth.

seem uncritical, since they are assumptions to the benefit of the BPH population. This is valid particularly for the first assumption: Pest control by mycoinsecticides would be much more effective if the BPH nymphs would be affected by infection too.

3.5.3 Critical modelling assumptions

The present model only has the BPH and Hirsutella populations as stock variables, while the BPH's antagonists are subsumed under the parameter c = predation being hold constant during any simulation run. Even if the predators are not affected by mycoinsecticides, they are concerned indirectly by the decrease of the BPH population that is their prey and food. It is important in this connexion, how much the predators are dependent on the BPH population as food:

- If the BPHs are the only prey of their predators, mycoinsecticides not only would decrease the BPH population but in consequence the predator population too. This effect is to the benefit of the BPH population in its turn. In this case the efficiency of mycoinsecticides might be strongly reduced compared to the present model.
- If the predators can choice their food such that they are able to survive without BPHs, they should not be much concerned about mycoinsecticides, and no positive effect on the BPH population is to be expected provided that Hirsutella citriformis is not lethal for the other preys too.

On the basis of observations in hand, we are proceeding on the assumption that the latter situation holds true. Otherwise, the interrelations of the BPH and its predator populations would have to be quantified and built into an extended model.

References

AGUDA, R.M., LITSINGER, J.A. & ROBERTS, D.W.; 1984: Pathogenicity of Beauveria bassiana on brown planthopper (BPH), whitebacked planthopper (WBPH), and green leafhopper (GLH). Intern. Rice Res. Newsl. 9(6): 20.

AGUDA, R.M., ROMBACH, M.C., SHEPARD, B.M. & ROBERTS, D.W., 1985: Mortality of adult brown planthoppers (BPH) in different types of cages used for bioassays of entomopathoge_nic fungi. Intern. Rice Res. Newsl. 10(2) 17-18.

BACALANGCO, E. & KHUSH, G.S., 1983: A technique for preparing rice plants for brown planthopper rearing. Intern. Rice Res. Newsl. 8(6): 15.

CARRUTHERS, R.I., LARKIN, T.S. & SOPER, R.S., 1988: Simulation of insect desease dynamics: an application of SERB to a rangeland ecosystem. Simulation 51(3): 101-109.

CHIU, S.C., 1979: Biological control of the brown planthopper. In: Int. Rice Research Inst. ed., Brown Planthopper: Threat to rice production in Asia. 335-355. Los Banos.

CONTI, M., 1985: Transmission of Plant Viruses by Leafhoppers and Planthoppers. In: NAULT, L.R. & RODRIGUEZ, J.G. (eds.): 289-307. Wiley, N.Y., Brisbane, Toronto.

DYCK, V.A. & ORLIDO, G.C., 1977: Control of the Brown Planthopper (Nilaparvata lugens) by Natural Enemies and Timly Application of Insecticides: The rice brown planthopper, Tokyo, 58-72.

FABELLAR, L.T. & HEINRICHS E.A., 1984: Toxicity of insecticides to predators of rice brown planthoppers, Nilaparvata lugens STAl. Environmental Entomology 13(3): 832-837.

FRANKI, R.J.B., FAUQUET, C.M., KNUDSON, D.L. & BROWN, F., 1991: Classification and Nomenclature of Viruses. Achives Virology 2, 195-197.

GREATHEAD, D.J., 1983: Natural enemies of Nilaparvata lugens STAL and other leaf- and plant-hoppers in tropical agroecosystems and their impact on pest populations. In: Proceedings of the 1. International Workshop on Biotaxo_nomy, Classification and and Biology of Leafhoppers and Planthoppers (Auchenorrhyncha) of Economic Importance. KNIGHT, W.J., PANT, N.C., ROBERTSON,T.S. & WILSON, M.R. (eds).

HOLDOM, D.G., TAYLOR, P.S. & SOPER, R.S., 1988: Activity of Ento_mophthoran Fungal Isolates (Zygomycetes) against Nilaparvata lugens and Sogatodes orizicola (Homoptera: Delphacidae). J. Invertebr. Pathol. 52: 221-230.

JEGER, M.J., 1983: The development of models for practical use in crop protection. Bulletin IOBC/WPRS;NS; VI(2): 1-78.

KAWAHARA, H.E. & KIRITANI, K., 1975: Survival and egg-sac formation rates of adult females of Lycosa pseudoannulata (BOES. & STR.) (Araneae: Lycosidae) in the paddy field. Applied Entomology and Zoology 10: 232-234.

KIRITANI, K., 1976: The effect of insecticides on natural enemies with particular emphasis on the use of selective and low rates of insecticides. Review Plant Protection Research 9: 90-100.

KURUVILLA, S. & JACOB, A., 1980: Pathogenicity of the entomogenous fungus Paecilomyces farinosus DICKSON et FRIES to several insect pests. Entomol. 5(3): 175-176.

LUENBERGER, D.G., 1979: Introduction to dynamic systems. Wiley, N.Y.

MUELLER-KOEGLER, E., 1965: Pilzkrankheiten bei Insekten. Parey, Berlin, Hamburg.

PALMER, L.T., 1978: Rice yield losses duce to brown planthopper and rice grassy stunt disease in Java and Bali. Plant Dis. Rep. 62(11): 962-965.

RAI, P.S. & CHANDRASEKHAR, H.T., 1979: The natural enemy complex of rice brown planthopper. Current Research 8(2):23-24.

RAMAN, K., 1983: Insecticide toxicity to natural brown planthopper enemies. IRRI 8(4): 20.

REISSIG, W.H., HEINRICHS, E.A. & VALENCIA, S.L., 1982: Effects of insecticides on Nilaparvata lugens and its predators: spiders Microvelia atrolineata, and Cyrtorhinus lividipennis. Environmental Entomology 11(1): 193-199.

ROMBACH, M.C., AGUDA, R.M. & ROBERTS, D.W., 1986: Biological Control of the Brown Planthopper, Nilaparvata lugens (Homoptera, Delphacidae) with dry Mycelium applications of Metarrhizium anisopliae Deuteromycotina; Hyphomycetes). Phillipp. Ent. 6(6): 613-619.

SAMSON, R.A., 1982: Laboratory culture and maintenance of entomopathogenic fungi. In: Proceedings XV. Annual Meeting Society Invertebr. Pathology and III Intern. Colloquium on Invertebr. Pathology: 182-184, Brighton, UK.

SANDERFUR, J.T., 1990: Discrete dynamical systems, Clarendon Press, Oxford.

SCHMIDT, B., 1985: Systemanalyse und Modellaufbau. Grundlagen der Simulationstechnik. Springer, Heidelberg.

SOPER, R.S., 1982: Commercial Mycoinsecticides. in: Proc. XVth Anm. Meeting Soc. Invert. Path., 98-102.

SOPER, R.S. & WARD, M.G., 1985: Production, Formulation and Application of Fungi for Insect Control. BARC Symp. 5, PAPAVIZAR, G.C. Ed. Allanheld Pub., 161-180.

UTHAMASAMY, S., VELU, V., GOPLAN, M. & RAMANATHAN, K.M., 1983: Incidence of brown planthopper Nilaparvata lugens STAL. on IR 50 at graded of fertilization at Aduthurai. IRRN 8(5):13.

Software

STELLA II, High Performance Systems, Inc., 1990

MATHEMATICA 2.2, A system for doing mathematics by computer, Wolfram Research, 1992