Alternatives of process approaches in agro-ecosystem modelling

PhD theses

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Corvinus University of Budapest, Dpt. of Mathematics and Informatics, 2006.

PhD School/Program

Name: Landscape Architecture and Decision Support Systems

PhD School of Multidisciplinary Agricultural Sciences

Field: Multidisciplinary Agricultural Sciences

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I. INTRODUCTION AND AIMS

The points of views about the general way and consequences of the climate change in progress are based more or less on the same principles. The details concerning smaller, special regions, however, can be quite different. While living under changing climate conditions, one of our most urgent tasks is to create well-designed descriptive-forecasting systems, as well as to define the optimal preparing and response strategies to the conditions in change. In the thesis the solutions of three problems in connected fields are given.

A. A population-dynamical biomass model of an agro-ecological food-web system

While considering the protection of environment according to the optimal economical management the plant - weather - pest system is investigated as a complex agro-ecosystem. A seasonal population-dynamical model of a simplified agro-ecological food-web system has been improved in such way, that the external effects on the whole agro-ecosystem, together with the interactions between the populations of the system can be examined. With the help of the biomass model the seasonal pattern of climate, as well as the biotic interactions between the populations are considered. The analytical model is structured by a deterministic difference equation system with daily steps.

B. The phenology model

During the research of the future of plant production and protection more and more specific and, at the same time, more and more general models are required to be found out and created in well-applicable form. The intensive research of the spatial-temporal dynamical models of pest populations and phenology can be a key element of the precision plant protection. By our second model, the daily numbers of individuals of the different phenophases of a population are defined, based on the daily biomass data of the populations, on the daily climate data, as well as on the characteristic data of the phenology and other biological property of the populations. The parameters of the simulation model have been calibrated by the data of four Sycamore lace bug (*Corythuca ciliata*) populations living in Budapest. The effect of the climate change on the Sycamore lace bug populations has also been investigated, by the most widely accepted climate scenarios.

C. The investigation of the risk of corn and wheat production in Hungary

Risk can be considered from several aspects of view depending on the role of the decision maker in the risky prospect. One of the most important tasks of the researchers in risk analysis is, to help the application of decision support systems and develop easy-available advisory systems with the help of information and electronic technology and theoretical results.

In the third part of the thesis it is proved that the risk of corn and wheat production in Hungary between 1950 and 1990 has been increased, partly independently to the risk aversion of the decision maker. In some region, moreover, the increase is quite high and became even quicker.

In addition to the new results, the mostly applied, rather wide scientific background of the research, which is not generally spread in Hungary, is introduced in a properly detailed way.

III. MATERIALS AND METHODS

1 Materials

Sycamore lace bug populations

The evaluation of our model was based on the data of four different sycamore lace bug populations (*Platanus hybrida* and *Corythuca ciliata* , Say, 1832, Heteroptera: Tingidae).

Corythuca ciliata was known as a kind of pest of several series of plane trees even in its original homeland, North America. The larvae are sucking the backside of the leaves in groups. It is the most harmful pest of park trees in Budapest, and its damage is becoming more and more serious. When choosing the species, its ecological advantages were also regarded.

Weather data

The applied daily average temperature data are from the monitoring database of OMSZ (*Hungarian Meteorological Service*).

Scenarios

The phenology model was run also for the daily average temperature forecasted by climate scenarios. During our research, we applied the principles defined by IPCC (***I****ntergovernmental* ***P****anel on* ***C****limate* ***C****hange*) and we used some of the most commonly accepted scenarios presented in international reports, such as

- Scenario BASE which is the base of all other scenarios with the parameters of our days.
- Scenarios GFDL2535 and GFDL5564 have been created by Geophysical Fluid Dynamics Laboratory (USA) with consideration of CO2 increase in atmosphere. The only difference between the two scenarios is, that the latest has a finer resolution.
- UKHI (***HI****gh-resolution equilibrium climate change experiment*), UKLO (***LO****w-resolution equilibrium climate change experiment*) and UKTR (*high-resolution* ***TR****ansient climate change experiment*) worked out by ***U****nited* ***K****ingdom* ***M****eteorological* ***O****ffice* (UKMO). We present the results of the 15th year of each 30-year period scenario concerning the years around 2050. The scaling of the scenarios for the region Hungary was made in the frame of CLIVARA project (*CLImate Change, Climatic VARiability and Agriculture in Europe*). The database and the references were made available for us by professor Zs. Harnos, the Hungarian leader of the project.

Crop results

To the risk analysis the data of the Hungarian regional yearly crop results of corn and wheat were applied. The data were gained from the database ***A****gro-ecological* ***I****ntegrated* ***I****nformatics System* (AIIR) (Gerenday et al., 1991).

2 Methods

Modelling

An agro-ecosystem is directed mainly by the interactions among the populations living in the system together. Several indirect or hidden types of interactions that cannot be expressed as different kinds of material flow, such as competition, the indirect interactions that can be derived from the escape from or the defence against a common predator, as well as the so-called 'top down and bottom up regulations' are involved in a food web.

In the first part of our modelling work a population-dynamical model completed with the most important abiotic effects has been created. To simulate the interactions, a discrete difference equation system with daily scale is used. The general equation of the food web model is based on three elements: the first one is to express the activity of the individual depending on the temperature, the second one is to describe the effect of the quality and the quantity of nutrient of the populations and the third one is to display the effect of the predators. The results are expressed in biomass units.

As in the literature, there are plenty of excellent models which describe certain parts of processes quite exactly, thus our aim was to create such a physiological and analytical model which describes the whole interaction process, in order to be able to apply it also in cases when detailed data are missing, and to extend it in cases when more complex data are available.

In the second part the model was further developed and calibrated for four sycamore lace bug populations (*Corythuca ciliata*, 1989, 1998, 1999) by optimization methods. Our model was written in an *MS Excel*® environment and optimized by *MS Excel*® *Solver*, which makes it easy to apply.

Risk analysis

The data of corn yield are fitted by nonlinear (logistic) regression. Then they are corrected by *MS Excel*® with the help of *Phyllips*-method in order to make them comparable. The subjective expectation, as well as the subjective standard deviation (E_s, D_s) are calculated based on experts' estimations. The corrected data are defined by $y_i^{korr} = f(x_{akt}) + \varepsilon_i$, where ε_i denotes the residuals of the logistic, regression, while $f(x_{akt})$ denotes the value of the regression function at the right endpoint of the regression domain. (The type of logistic regression was chosen not only because of its excellent fitting properties (R^2, ANOVA, t values for the coefficients), but also because of the changing producing technologies between 1970 and 1973.)

The values y_i^{korr} can be weighted by p_i the following way: based on experts' estimation the probability of the occurrence of the year i, is calculated. It is obvious that $\sum_i p_i = 1$. Denote by E_t and D_t the expectation and the standard deviation of y_i^{korr}, respectively. The current data can be gained as follows:

$$Y_i + \frac{y_i^{korr} - E_t}{D_t} \cdot D_s$$

It is evident that $E(Y_i) = E_s$ and $D(Y_i) = D_s$.

The subjective distribution functions were calculated based on experts' estimations.

As the exact personal risk aversion was not known, we used the widely applied negative exponential utility function $U : w \mapsto U(w) = 1 - \exp(-cw)$. The most important property of this function is that its absolute risk aversion r_a is constant while its relative risk aversion r_r is linearly dependent of wealth w

$$r_a(w) = c \qquad\qquad r_r(w) = cw$$

Three efficiency criteria were considered, namely: the stochastic dominance based on the subjective distribution functions, The E,V - efficiency as well as the criterion based on the utility function. However, the results have not fulfilled all of our expectations. The risk increase was finally proved by a recently simplified variant of the general stochastic dominance criterion.

IV. RESULTS

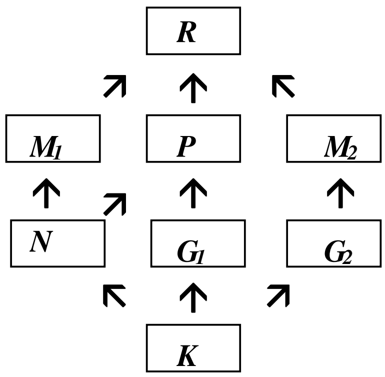
A. A population-dynamical biomass simulation model of an agro-ecological food-web system

1 General description

To develop our model a simplified food web model was considered (see Figure).

On the first level, K denotes the water and nutrient content of soil, as the input of the system. Above the source term there are a cultivated plant, denoted by N, and two kinds of weed, denoted by G_1 and G_2, respectively. On the third level, monophagous M_1 consumes the cultivated plant N, while monophagous M_2 eats one of the weeds. P denotes a polyphagous pest which consumes the cultivated plant N, as well as weed G_1. Additionally, there is a predator, denoted by P, that consumes pests M_1, P and M_2.

The dynamical changes of the biomass of the populations as well as the interactions between the populations are described by the model.



A food web model. The interactions amongst the source (K), the cultivated plant (N), the weeds (G_1 and G_2), the monophagous (M_1 and M_2) and the polyphagous (P) pests, as well as predator (R). (The arrows run from the nutrient to the consumer.)

2 The population dynamical model of the food web

To describe the interaction in the food web, a daily scaled, discrete difference equation system with seven equations is used, each of them is for a certain element N, G_1, G_2, M_1, M_2, P and R of the system at the ($t+1$)th point of time. The general form of the difference equation is

$$X_{t+1} = X_t \cdot R_{X,t} \cdot P_{X,t} \cdot F_{X,t}$$

where the current amount of the biomass of one of the populations N, G_1, G_2, M_1, M_2, P and R at the ($t+1$)th and tth points of time are denoted by X_{t+1} and X_t, respectively; the activity term of the individual X is denoted by $R_{X,t}$ (it is depending on the daily average temperature T); $F_{X,t}$ denotes the so-called nutrient term while $P_{X,t}$ denotes the so-called predation term. In what follows the terms of the general equation are shortly characterized.

The activity term $R_{X,t}$

The activity term $R_{X,t}$ is a function which expresses that the individuals do not develop under low temperature circumstances; while the temperature is increasing, the individuals are developing at a more and more rapid rate until a certain point; at higher temperature as it is optimal the development is impeded peculiarly to the individual. The range of the function is a narrow interval around the number 1. In case the daily average temperature is unpleasant for the individuals of X we have $R_X < 1$; if the daily average temperature is pleasant for X, then $R_X < 1$; for optimal conditions R_X is maximal.

The predation term P_X

The predation term P_X satisfies the following properties of the biomass-change:

- While the biomass of the consumer-population is increasing, the nutrient-population is decreasing at a slower and slower rate and, at the same time, the decreasing amount of the biomass of the nutrient-population is an impeding factor for the consumer-population. While the consumer-population is increasing slower, stagnating or decreasing, however, the amount of the biomass of the nutrient-population is going to stagnate or even increase.
- Consider the case of poliphagy. From the one nutrient-population's aspect the effect of the other nutrient-population is, in one hand, positive (while the other is consumed, the one can escape), in the other hand, it is negative (the other nutrient-population is making the consumer-population stronger by nourishing it).

The above effects of the interactions are quite complex. Our aim was to give the simplest model ever which describes the above properties as exactly as possible.

The nutrient term $F_{X,t}$

Nutrient term $F_{X,t}$ is due to performance the following properties of the individuals in the model:

(i) In the case a nutrient is unlimitedly available (under fixed other circumstances), the biomass of X is increasing at a maximal rate denoted by $\mathcal{K}_X$.

(ii) In the case a nutrient is limited, the biomass of X is increasing more slowly, stagnating or decreasing.

(iii) In the case a nutrient is just as much as needed, the amount of the biomass is nearly constant ($F_X \approx 1$).

(iv) In the case a nutrient decreases excessively, the individual is going to die ($F_X \to 0$).

(v) In the case the individual is in competition with another consumer, the change of biomass is influenced by the amount of the biomass of the other consumer together with some weight parameters.

(vi) A polyphagous (P or R) consumes from the different populations in proportion to the amounts and the nutritive values of its nutrient-biomasses.

3 A case study

The model described above was tested with real temperature data together with fictious but real proportional starting values K_0, N_0, G_{1_0}, G_{2_0}, M_{1_0}, M_{2_0}, P_0 and R_0. Both the one- and the five-year simulation results were based on the daily average temperature data measured in Debrecen, Hungary, in 1980 and between 1980 and 1984, respectively.

B. The phenology model

1 Introduction

The above model describes the biomass dynamics of the populations of a simple food web. Applying the model, an obvious question is how the number of individuals can be derived from a given amount of biomass. More exactly, if the phenological phases of the population, together with their biological properties, are known, how can one define the number of the individuals in the phases at a given point of time? Our second model is to solve this problem.

2 The activity term R_t and the cumulated activity term $\underset{t \geq t_s}{cum} R_t^{Ph}$

The value of activity term R_X is depending on the daily average temperature T via the point of time t. It expresses how (positively or negatively) the daily average temperature effects on the individuals of a certain population. In what follows we suppose that the agro-ecological process is not defined by the daily average temperature itself, but also by the phenology of the considered individuals of X, because the effect of the same temperature on the individuals can be very different in different phenological phases.

To express this more sophisticated effect we called for the well-known idea of 'temperature-sums' and introduced the concept of the so-called cumulated activity $\underset{t \geq t_s}{cum} R_t^{Ph}$. Cumulated activity $\underset{t \geq t_s}{cum} R_t^{Ph}$ depends of a point of time t and the current phenophase Ph and it is expressed in unit °C. The values of $\underset{t \geq t_s}{cum} R_t^{Ph}$ can be calculated with the help of a characteristic function SW_t^{Ph}. The characteristic function SW_t^{Ph} is defined as follows:

$$SW_t^{Ph} = \begin{cases} 0 & \text{, if } Ph \text{ true} \\ 1 & \text{, if } Ph \text{ false} \end{cases}$$

It means that if at a point of time t the considered population has its individuals in phenophase Ph (Ph is true), then $SW_t^{Ph} = 1$, and it is equal to zero else. It is assumed, however, that the phenophases of a population follow each other discretely, that is to say the metamorphosis from a phase to another one proceeds at once. Thus, the whole population consists of individuals of an only type of phenophase. (This condition will be omitted in the next step.)

3 The smoothed characteristic function SSW_t^{Ph}

It is obvious that there must be a point of time a phase is entered first, and there must be another one at which the process of metamorphosis is finished for the whole population. This means that function $SW_{X,t}^{Ph}$ that 'switches' on/off the phases has to be smoothed such that we can express that the metamorphosis is a process and there are more phenophases existing at the same time.

SSW_t^{Ph} is constructed such that it can also describe the proportion of the biomass of the individuals of the different phenophases within a population.

4 The function NoI_t^{Ph} for the number of individuals of the phenophases

Based on the current biomass amount the function NoI_t^{Ph} defines the number of individuals of the phenophases at a given point of time t. It is suitable to express the following properties of the populations:

1. The sum of the numbers of individuals does not increase in any time except in imago phase.
2. During the metamorphosis from a phase Ph into the next one, denoted by $Ph+1$, the number of individuals in phase Ph is decreasing tending to 0, while the number of individuals in phase $Ph+1$ is increasing.
3. The mortality caused by the metamorphosis should be considered.
4. The decrease of the biomass of X can be caused
   - on the one hand, by the fact the individuals are losing/putting up weigh (short/plenty of source)
   - on the other hand, by mortality

   The number of individuals, in the first case, does not change, while, in the latter case, it is decreasing.

Comparing the empirical data of the number of larvae and imagos per leaf with the one predicted by the model we can see that the model fits the data very well. It follows the shape of the two-generation population as well as the time and rate of maximum. The model, however, contains much more information that is hardly or not measurable at all.

5 The expected phenological pattern of sycamore lace bug based on climate scenarios

The phenological patterns of sycamore lace bug populations predicted by the model with six different climate scenarios (Basic, GFDL2535, GFDL5564, UKHI, UKLO, UKTR) containing the daily average temperature for 30 years were compared. The results are presented for the year 1999 as well as for the 15th year of each scenario because we found it quite typical. The daily average temperature, the activity terms R_t, the graphs of the smoothed characteristic functions SSW_t^{Ph} and the one of the function NoI_t^{Ph} for the number of individuals of the phenophases, moreover, the average numbers of larvae and imagos per leaf are displayed and analysed.

6 Generalizations of the models

The models can be generalized several ways. Three of them are given in the thesis in details. These are:

- the generalized phenology together with the generalized characteristic function,
- the generalized biomass model and
- the generalized function for the number of individuals of the phenophases.

C. The risk analysis of corn and wheat production with a new stochastic efficiency method

1 Introduction

In agriculture we face several decision problems in which, among proficiency and sustainability, the risk aspects have to be investigated more and more seriously. In Hungary the risk of production is especially meaningful as it has considerably been increased in the last few decades. In the thesis we proved that the risk of corn and wheat production increased between 1951 and 1990 in four Hungarian counties (Hajdú-Bihar, Bács-Kiskun, Fejér and Győr-Moson-Sopron), independently to rate of risk aversion. In some regions the rate of increase became even quicker. The further research was impeded by data deficiency.

2 The risk analysis of corn production in four Hungarian counties (1951-90)

Efficiency criteria

Observing the graphs of corn yield we can recognize that beside the yield loss caused by the Hungarian political situation at the end of the eighties, the deviation of the yield started to become greater yet at the beginning of the eighties. There was a heavy yield loss in 1990, thus we investigated the problem in two ways:

- with tree times twenty years (1951-70, 1961-80, 1971-90) and
- leaving out the year 1990, with a shortened data series (1951-70, 1961-80, 1971-89).

Using the current data calculated on the basis of experts' estimations (for the method see section III.) we defined the subjective distribution functions for the four counties and for the time intervals 1951-70, 1961-80, 1971-90/89.

Stochastic dominance, *E,V* - efficiency and the criterion based on the utility function

In Bács-Kiskun, while the expectation was decreasing, the deviation was increasing (the subjective distribution function shifted left, its slope increased). For the other counties the change is not so evident. In Bács-Kiskun the E,V - efficiency method gives the same result for the whole time intervals. For the other counties and for Fejér with the truncated data the E,V - efficiency method does not make any order.

Together with E,V – efficiency the linear functions

$$U_{CE} : V_i \mapsto U_{CE}(V_i) = CE + 0.5 r_a V_i$$

were also defined for absolute risk aversion value $r_a = 0.004$ and for three fixed certainty equivalent (CE) values. In every case we got that the situations become worse with time. The disadvantage of the method based on utility criterion is, however, that it makes an order for fixed absolute risk aversion, only. For more information we should call for the more general stochastic efficiency criterion.

Stochastic efficiency

Comparing the time intervals 1951-70 and 1961-80, applying the stochastic efficiency criterion we proved that the risk of corn production has increased in all the four counties, independently from the rate of absolute risk aversion r_a. The risk for time interval 1971-90 has increased even more in all counties but Győr-Moson-Sopron, especially for greater r_a values.

We can ask whether this risk increase is caused only by the heavy yield loss of 1990. Using the truncated data we can see that the rate of risk increase is less, but evident, especially for greater r_a values.

For the truncated data we calculated again the certainty equivalent (CE) values depending on the absolute risk aversion r_a. We got that the time series with the less risk was the earliest (1951-1970). In Hajdú-Bihar and Fejér the risk increase holds only for $r_a > 0.002$. This fact, however, does not make the importance of the objective warning less serious.

The risk increase was the greatest in Bács-Kiskun and the less in Győr-Moson-Sopron, but the fact of risk increase is obvious everywhere.

3 The risk analysis of wheat production in four Hungarian counties (1951-90)

The efficiency criteria

First the subjective distribution functions are defined for the four counties and for the three times twenty years. In this case the use of truncated data was not reasonable.

Stochastic dominance, *E,V* - efficiency and the criterion based on the utility function

The most evident risk increase of wheat production was in Hajdú-Bihar. The subjective distribution functions are ordered here pointwise. The same can be proved with the $E,V-$ efficiency method, though with this method we get no ordering for the time intervals in the other three counties. The criterion based on the utility function gives the same ordering for the three time intervals in all counties but Fejér. This proves the risk increase obviously, though, only for a fixed r_a value.

Stochastic efficiency

Comparing the time intervals 1951-70 and 1961-80, applying the stochastic efficiency criterion we proved that the risk of wheat production has increased in all the four counties, but Fejér, independently from the rate of absolute risk aversion r_a. In Fejér the less risky interval was 1951-70 and the most risky one was 1961-80 for almost the whole domain of r_a. The risk increase was the greatest for 1971-90 only if $r_a > 0.014$.

The rate of increase became greater only in Győr-Moson-Sopron, but independently from r_a.

The kurtosis of the distribution function of corn yields was always positive. It was not the case for wheat yields; where the kurtosis decreased with time. The difference is the following: the deviance of the distribution of wheat yield, has increased slowly; for corn yield, however the change manifested with serious extreme values.

D. The list of the new results

A. The development and analysis of a population-dynamical biomass model of an agro-ecological food-web system based on a discrete, deterministic difference equation system

- The model description of predation, competition and source dependency, together with the one of bio-activity as a function of the daily average temperature
- The mathematical proof on the biological functions of the physiological and analytical model
- The evaluation of the model
- A one-year theoretical case study of the simulation model results based on the daily average temperature data measured in 1980 in Debrecen, Hungary
- A five-year theoretical case study of the simulation model results based on the daily average temperature data measured between 1980 and 1984 in Debrecen, Hungary

B. The phenology model of the populations of an ecosystem with the function of the daily number of individuals of the phenophases based on the daily weather and biomass data and other biological properties

- The generalization of the activity term, depending on the phenology
- The definition of the cumulated activity
- The definition of the characteristic function that express the phenology changes; the smoothed generalization of the characteristic function
- The calculation of the number of individuals in each phenophase
- The expected phenological pattern of sycamore lace bug based on climate scenarios
- Comparison of the empirical data of the number of larvae and imagos per leaf with the one predicted by the model
- Further generalizations of the phenology model (generalized phenology, generalized characteristic function, generalized biomass model and generalized function for the number of individuals of the phenophases.

C. The risk analysis of corn and wheat production in four Hungarian counties (1951-90)

- The proof on the increase of risk with the application of known efficiency criteria as well as with a newly published general stochastic criterion

V. CONCLUSIONS

1 Applications

The population dynamical model of the agro-ecological food web model was investigated in case of spatial inhomogeneity by Horváth (2002). His results can well be applied in precision agriculture.

An application of the multivariate state plane systems is based on our food web model (Horváth et al., 2003).

Because of lack of data of sufficient quality and quantity the model evaluation presented in the thesis is incomplete. Both of our models are, however general enough to describe the dynamics of the simple Hungarian ecosystems or the phenology of several plant-pest systems. We expect that using the data of current system monitoring we can validate and evaluate our models for further systems.

The application of the phenology model is expected in plant protection. With the model, based on the weather parameters up to a certain point of time we can define the optimal date at which the maximum of the most sensitive phenophase is expected. Moreover, as the model is suitable for biomass/number of entities estimations as well, so not only the date but also the optimal amount of chemicals can be defined more precisely.

Though biological plant protection is not widely spread in Hungary, it could be well-supported by the application of both of our models.

4M has been developed by the *Hungarian Agricultural Model Designer Group*. It contains several models to describe the physiological interactions of soil - plant systems. We plan to complete it with a plant - pest model module that is going to be developed from our models.

2 Further plans

- Investigation of long-time (20-40-year-long) series
- Prognosis based on simulated input data

In the above two cases the correction of scaling can be needed: in vegetation period we can use even an hourly-step model.

- Comparison of the stability of the models in short- and in long-time situations
- Generalizations for highly complex food web systems with great volume populations and expansion

To this we need to structure and/or simplify the models with multivariate methods. Moreover, the models should be generalized and/or specialized in some points of view.

- Stochastic and spatial generalization
- Risk analysis of plant - pest systems
- Spatial extension of the models for inhomogeneous or patchy environment

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