The impact of climate change on phenology and population dynamics of Geometridae (Lepidoptera) species

Theses of PhD Dissertation

Zsuzsanna Kúti

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Doctoral School: **CORVINUS UNIVERSITY OF BUDAPEST**
Landscape Architecture and Landscape Ecology

Field: **Agricultural Technology**

Head of PhD School: **Prof. Attila Csemez, DSc**
CORVINUS UNIVERSITY OF BUDAPEST
Faculty of Landscape Architecture
Dept. of Landscape Planning and Regional Development

Supervisor: **Dr. Ladányi Márta, Phd**
CORVINUS UNIVERSITY OF BUDAPEST
Fakulty of Horticulture Science
Department of Biometrics and Agricultural Informatics

The applicant met the requirement of the PhD regulations of the Corvinus University of Budapest and the theses are accepted for the defence process.

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Head of Ph.D. School **Supervisor**

1. INTRODUCTION AND AIMS

Invertebrates, mainly insects and arthropoda, make up over three quarters of the known animal species. Their communities play an important role not only in the biodiversity of our planet, but they have a fundamental effect on how near-natural and agricultural ecosystems work. The pollination of flowering plants, pest insects, arthropoda maintaining soil processes, or pests related to human, animal and plant health care issues are perfect examples.

Climatic changes have a significant effect on the structure of insect communities, the compounds of regional fauna, and the seasonal coenological changes in the state of certain local habitats (microhabitats, biotopes). Weather has a direct impact through phenological and population dynamics processes, which will indirectly affect the changes in area and biodiversity.

Invertebrate communities are important not only in themselves – they are effective indicators of the impact of climatic changes, in point of both environmental and nature conservation and agriculture. They provide information which other methods would not produce, or would be very hard to obtain otherwise.

Research into climatic demand, phenology, and the impact of climate change yields information that can be utilized in the field of pest control and forest conservation as well.

Population dynamics examinations of geometer moths based on recorded damage have significant importance in pest control when investigating the protection of both forests and fruit trees. Some species of this moth group belong to those insects that cause total defoliation in the largest areas. Thanks to the forest light trap network installed in 1961 we have at our disposal a set of recorded data which cover a long period, although the recording criteria applied in the different periods were not always uniform. Processing and examining these data is an urgent task in order to understand these species better and to map the expected future changes.

Using the accessible data and scientific information I examined the outbreak dynamics of eight univoltine (one generation per year) Lepidoptera species as reflected by the climate change.

Four of them are pests whose examination is regarded as a priority by international experts as well. The other four are not pests, but they contribute to the many-faceted Hungarian fauna and have not been examined from this point of view either in Hungary or abroad. Moreover, there is little information concerning their faunistic features either.

Based on the above facts, I formulated my aims as follows:

1. Describing the time distribution of the beginning and length of the outbreak, estimating future modifications in the beginning and length of the outbreak on the basis of climate models.
2. Designing a system of species-specific climatic indicators whose close connection to the outbreak dynamics of the species can be proved.
3. Approximating the annual number of individuals using population dynamics models based on differential equations.
4. Expanding these population dynamics models with climatic indicators to improve the estimate of annual number of individuals.
5. Identifying and describing the principles in the population dynamics of the species, depending on the accessible weather parameters and the climatic indicators formed from them, and those hidden in the phenological events of the individual populations.
6. Estimating regional climate models and forming statements concerning the predicted number of individuals of species based on climatic indicators and population dynamics models, extended with the climatic indicators.

2. MATERIAL AND METHOD

2.1. RESEARCH MATERIAL

In order to analyse the past and future impact of climate change we need long term meteorological and trapping data sets. The trapping data used in the research come from 46 years of data collected by 9 traps of the National Forestry Light Trap Network which were operational the longest, from 1962 to 2006. In the study, I used data of such univoltine Geometridae species whose individuals were trapped every year. From among the Lepidoptera, the order with one of the highest number of species, I selected four forest and horticulture pests and four which are not pests.

The meteorological data are daily records from 1961-2000 from the National Meteorological Service database. To examine the impact of the climate change, I used the results gained when executing the RegCM3.1 (regional) climate model adapted by the researchers of the Department of Meteorology of Eötvös Lorand University, Budapest.

2.2. RESEARCH METHOD

2.2.1. THE TRAPPING DATA PROCESSING

It was reasonable for all data uniformly light traps used to reduce the number of amendments to various abiotic factors and effects for swarming capture data used in the tests, which were carried out moving-average calculation.

2.2.2. EXAMINING HOW THE BEGINNING AND THE LENGTH OF THE OUTBREAK DEPEND ON EACH OTHER AND ON THE CLIMATE FACTORS

I examined the interdependence of the beginning and the length of the annual moth outbreak, and their dependence on the climate factors. Using the accessible sample, first I investigated the relationship between the beginning and the length of the outbreak of the species in question on the basis of the outbreak data and the 11-year moving average between 1972 and 1988. Next, applying logistic regression to the 17-year period I analysed the trends in the beginning and length of the outbreak. The statistical analysis was performed using PASW Statistics 18.0.

2.2.3. POPULATION DYNAMICAL MODELS BASED ON DIFFERENCE EQUATIONS AND INDICATOR ANALYSIS

I developed three models:

1. The basic population dynamical model of the annual number of individuals based on difference equations
2. The basic population dynamical model extended by climatic indicators
3. The basic population dynamical model extended by proncipal components of climatic indicators

The basic model

I set out from a simple discrete population dynamical model (sometimes called the theta-logistic model):

where is the number of individuals in year t+1, which, through an exponential function, depends on the number of individuals in the previous year , on the maximal growth rate , on the carrying capacity K and on the power parameter .

Introducing the notation as:

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we can rewrite the above formula as:

with .

Fitting and validation procedure

The root mean square error (RMSE) was defined as the root of the average sum of the squares of the differences between the observed ( ) and model predicted ( ) values:

where n denotes the number of years. RMSE was minimized while three parameters, namely the maximal growth rate , the carrying capacity K and the power parameter were varied. For optimization we used Palisade's Risk Evolver that is based on innovative genetic algorithm (GA technology), a stochastic directed searching technique with several thousands of iteration.

Climatic Indicator Data Set

From the meteorological daily data we calculated climatic indicators. We cut the 365 or 366 days of the years into decades (of ten days) and for a year t we calculated

- the average of the daily mean temperatures of the i^{th} decade (TMt_i)
- the average of the daily minimum temperatures of the i^{th} decade (TNt_i)
- the average of the daily maximum temperatures of the i^{th} decade (TXt_i)
- the average of the daily precipitation of the i^{th} decade (Pt_i)
- the minimum of the daily minimum temperatures of the i^{th} decade (TNNt_i)
- the maximum of the daily maximum temperatures of the i^{th} decade (TXXt_i).

We also calculated the monthly climatic indicators as well:

- the average of the daily mean temperatures of the j^{th} month (TMmt_j)
- the average of the daily minimum temperatures of the j^{th} month (TNmt_j)
- the average of the daily maximum temperatures of the j^{th} month (TXmt_j)
- the average of the daily precipitation of the j^{th} month (Pmt_j)
- the minimum of the daily minimum temperatures of the j^{th} month (TNNmt_j)
- the maximum of the daily maximum temperatures of the j^{th} month (TXXmt_j).

For t=1962, ..., 2000 the vector was correlated with all the climatic indicator vectors and to find the connection between the population change from the year t to the year t+1 denoted by and the indicators of the year t+1 and the ones of the previous year t. The indicators with significantly high correlation values R^2 were selected. We have found some highly correlated indicators referring consecutive decades, thus we completed the indicator set with some extra indicators called summer (calculated from 20th of July to 15th of August) and fall (calculated from 15th of October to 15th of November) indicators as follows.

Between 20th of July and 15th of August:

- the average of the daily mean temperatures (STM*t_i*)
- the average of the daily minimum temperatures (STN*t_i*)
- the average of the daily maximum temperatures (STX*t_i*)
- the average of the daily precipitation (SP*t_i*)
- the minimum of the daily minimum temperatures of (STNN*t_i*)
- the maximum of the daily maximum temperatures (STXX*t_i*) and

between 15th of October to 15th of November:

- the average of the daily mean temperatures (FTM*t_i*)
- the average of the daily minimum temperatures (FTN*t_i*)
- the average of the daily maximum temperatures (FTX*t_i*)
- the average of the daily precipitation (FP*t_i*)
- the minimum of the daily minimum temperatures (FTNN*t_i*)
- the maximum of the daily maximum temperatures (FTXX*t_i*).

The climatic indicators that showed significantly high (Person's) correlation with the number or the change of the number of individuals were selected.

Model development

Besides descibing the basic structure of the effect of endogenous and exogenous forces, with a more sophisticated model, we can express the impact of the climatic indicators as well. With this step we aimed to refine the model for a better fitting solution. The form of the model is:

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where are climatic indicators, are parameters to optimize.

First we took an only climatic indicator , the one which has the highest correlation with the vector . The root mean square error was minimized with innovative genetic algorithm while three plus one parameters, namely the maximal growth rate , the carrying capacity *K* and the power parameter together with were varied in the parameter space. Then we took a second climatic indicator from the indicator data set, the one which has the highest correlation with the vector being independent from the indicator(s) yet involved. Again, the root mean square error was minimized while one more parameter together with the formerly optimized four ones were varied. In each step we calculated the Akaike Information

Criterion with a Bayesian bias-adjustment in case the number of parameters *k* is large relative to the number of cases *n* ( ), which is the case we faced:

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where *k* denotes the number of parameters, *n* is the number of fitted values (years).
We went on with more and more climatic indicators involved in the model step by step and calculated the Akaike Information Criterion. The model was selected as the best one which had its lowest value.
Moreover, in each step we calculated the explained variance ratio as well:

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where denotes the average of the observed values.

2.2.4. PRINCIPAL COMPONENT REGRESSION

Regression analysis is used to look for a functional relationship between a dependent variable and one or more explanatory variables. The assumption of the method that the explanatory variables are independent from each other, i.e. collinearity does not hold. If this is not the case, then it might be necessary to use a dimension reduction method prior to the regression analysis. This can be performed with the help of the principal component analysis.

Principal component analysis is a multivariable analysis procedure which, with the help of linear combination of the independent variables (principal components), reduces the initially high number of highly correlating variables into a considerably lower number of independent variables. Regression analysis combined with principal component analysis is called principal component regression.

I calculated the significance level of the correlation coefficients and run an ANOVA test. To test the quotient of the estimate and its standard deviation, I did a Student's t-test.

For the statistical analysis, I used SPSS 20, while for the optimization procedure, Palisade Optimizer.

2.2.5. ESTIMATES FOR THE FUTURE

I compared the values of the climatic indicators based on estimates of the RegCM3.1 regional climate model and the observed number of individuals with that estimated by the models. I calculated the principal factor values based on the climatic indicators and the results of the principal component analysis using the prognosis of the RegCM3.1 regional climate model for the periods between 1961-1990, 2021-2050 and 2071-2100, and estimated the number of individuals.

For the statistical hypothesis tests I used one and two-sample t-tests, paired t- tests and Welch's t-test.

3.RESULTS

3.1. CO-DEPENDENCE OF THE BEGINNING AND LENGTH OF OUTBREAK AND DEPENDENCE ON CLIMATIC FEATURES

When examining the co-dependence of the beginning and the length of the outbreak, we could identify a significant negative linear correlation between the beginning (Julian Day) and the length (days) of the outbreak. Examining the eight species, we found that the later the imago appears, the shorter the outbreak is.

OPEROPHTERA BRUMATA (L.) - DETAILED RESULTS AND ANALYSIS

Low spring temperatures in the larvae activity period induce smaller imago populations and a later outbreak. Large amounts of rain and subsequent cold/freezing weather promotes the beginning of the outbreak. The most beneficial as to the outset of the outbreak is milder weather after the first frosts, as the indicator of the minimum temperature in early November shows significant negative correlation with the beginning of the outbreak.

Regarding the observed frequency and the one estimated for 2021-2050 using the RegCM 3.0 model, even more late outbreaks can be expected in the 2021-2050 period. Compared to the ones observed, the beginning of the outbreak can be delayed by 9 days. The frequency of extremely late beginnings of outbreaks is expected to increase, combined most probably with very short lengths.

3.2. POPULATION DYNAMICS MODELS

The estimates of the population dynamics models compiled for the observed nearly 40-year-long interval (1962-2000) appear to have been accurate. Thanks to the significant linear relationship between the number of individuals or its change and the various climatic indicators, the indicators or the main components derived from their linear combinations could considerably improve the basic model. In the case of

- ***Operophtera brumata*** The basic model was improved by the maximum of the mid-March daily maximum temperature of the previous year.
- ***Erannis defoliara*** For a better estimate of the number of individuals the basic model was completed with the precipitation in February and March in the year prior to the outbreak; the highest temperature in the second half of December, the mid-April average temperature and the lowest April temperature of the year examined, the highest temperature in August, and the precipitation in late October - early November and in the second half of December.
- ***Colotois pennaria*** The model was completed with the precipitation in February of the year before the outbreak; the highest temperature in April; mid-August precipitation; the maximum temperature in late October - early November; the minimum temperature in November; the average temperature in late November - early December; the lowest temperature in December, and the highest in the second half of the month; the mid-April average temperature of the year examined; precipitation in August; the mid-November minimum temperature and the maximum temperature in late November - early December.
- ***Erannis aurantiaria*** The basic model was improved with the late October - early November precipitation values.

About the next four species there are no worthwhile Hungarian publications discussing the climatic factors and their impact on the species.

- ***Idaea dimidiate*** The estimate of the number of individuals was improved when we added the coldest early January temperature of the previous year; the early February, mid-April and late June minimum temperatures; mid-September precipitation; the maximum temperature in late October - early November; and the March precipitation of the year examined.

- ***Scopula nigropunctata*** The basic model was completed with the late June and mid-November minimum temperatures; the late August - early September lowest temperature; and the late February precipitation values of the year examined.
- ***Pelurga comitata*** The estimate of the number of individuals was improved by adding the precipitation of the last week in January, the mid-April minimum temperatures, the lowest temperature in late July, the highest temperature in mid- August, the precipitation in late August, the mid-December minimum temperatures of the previous year, and the early January, mid-March and mid-April lowest temperatures, the minimum temperatures in the last three weeks of April, the average temperature and precipitation in April (i.e. the indicators of the average, minimum, and lowest temperatures and of the precipitation in April), and the highest temperatures in late October - early November.
- ***Eulitis pyraliata*** the basic model was completed with late January, mid-March, late November - early December precipitation, and end of April highest temperature from the previous year, and April minimum temperature and precipitation, highest temperatures in end of April, early June, and second half of September, late August - early September lowest temperatures, mid-November minimum temperature, mid-December precipitation and end of December maximum temperature from the year examined.

3.3. A COMPARISON OF THE CLIMATIC INDICATOR VALUES FROM ESTIMATES BY THE REGCM 3.1 REGIONAL CLIMATE MODEL AND OF THE OBSERVED AND MODEL-ESTIMATED NUMBERS OF INDIVIDUALS

The basic models, the models extended with indicators, and the ones completed with principal components produced the following prognosis for the minimum and maximum values of the number of individuals of the species, running the models with the climatic indicators estimated by the RegCM3.1 regional climate model:

- ***Operophtera brumata:*** The short-term estimate (2021-2050) shows a minimal increase in the number of individuals, while the long-term estimate (2071-2100) is a drop. Regarding the estimated maximum values, an increase is predicted in the 2021-

2050 interval, compared to the 1961-1990 reference period, and, moreover, further significant increase in 2071-2100.

- ***Erannis defoliaria:*** The estimated minimum and maximum values predict significant decrease both in the 2021-2050 and in the 2071-2100 intervals.
- ***Colotois pennaria:*** When comparing the minimum number of individuals estimated by the model to the reference interval (1961-1990), we can predict a small, short-term increase but in the longer term (2071-2100) the model predicts a significant drop in the number. A similar decrease can be seen when examining the maximum values.
- ***Erannis aurantiaria:*** The estimated number of individuals is expected to increase in the short term. However, in the long term changes in the value of the precipitation indicator might lead to a drop in the number of individuals. When comparing the estimated minimum and maximum numbers of individuals in the different periods, we can see that with a starting number, based on estimations by the extended model, a lower number is predicted for the 2071-2100 period, although there might be a short-term increase in 2021-2050.
- ***Idaea dimidiata:*** When comparing the minimum number of individuals in the different intervals, we can see that with a given starting number the growth will become smaller and smaller. Considering the maximum values, a decrease is expected in both the 2021-2050 and the 2071-2100 intervals. A comparison of the intervals shows that the number of individuals will increase at a lower and lower rate.
- ***Scopula nigropunctata:*** Regarding the estimated minimum number of individuals, in the short term in the 2021-2050 interval up to a starting number of 400 the number of individuals in the following year is expected to increase, but above 400 it may start going down. In 2071-2100, a similar change might happen already at 350 starting number of individuals. Regarding the estimated maximum values, we can see that up to the starting number of 1300 the number of individuals in the following year might be higher, but above that number it might start going down. In 2071-2100 the number of individuals can start increasing already at 800. All in all, neither the near nor the farther future are too promising for the species.
- ***Pelugra comitata:*** When analysing the estimated minimum values we can expect a drop in the numbers of individuals in the short term. In the 2071-2100 interval, the number might go up a little. A change in numbers is expected for each interval up to a starting number of 100 the model predicts an increase in the following year. Regarding

the maximum values the number is expected to go down in 2021-2050, then stagnate in 2071-2100.

- ***Eulithis pyraliata:*** Regarding the estimated number of individuals, it is true for each period that the minimum number of individuals is expected to go down by the next period. When looking at the maximum values, we can see that the number can increase in both 2021-2050 and 2071-2100.

3.4. NEW AND NOVEL FINDINGS OF THE RESEARCH

1. In my research, I investigated the changes in the beginning of the outbreak, and the correlation of the beginning and the length of the outbreak for four pest species *(O. brumata, C. pennaria, E. aurantiaria, E. defoliaria)* selected from the data collected by the National Light Trap Network in 1962-2000. For 1972-1988, I used a logistic regression model of time fitted to the beginning and the length of the outbreak. I concluded that there is significant linear negative correlation between the beginning and the length of the outbreak. It is true for all four species that the later the imago appears, the shorter the outbreak is. My research reveals that in the case of *O. brumata*, a notorious pest, the distribution of the observed beginnings of the outbreaks predicts even more late beginnings in the period between 2021 and 2050. Furthermore, the range of the outbreak beginning is expected to expand by 9 days, compared to that observed. The frequency of extreme late (mid-November) beginnings, combined with very short outbreaks, is expected to increase, too.

2. For the eight moth species involved in the study, I designed a phenology-dependent system of indicators for each specific species, whose significant correlation with the number of individuals and the changes in this number has been proved.

3. To follow changes in the number of individuals, for the eight moth species involved in the study I designed a simple population dynamics model based on a differential equation. Then I completed this to create a more sophisticated population dynamics model which takes into account species-specific climatic parameters as well. Comparing the estimates of the basic model and of the one extended with climatic indicators, I revealed that the results provided by the latter are more accurate. When analysing the data from the 39-year period for the eight moth species in the study,

examining the climatic indicators created for 37 decades and 12 months per year I could identify what can prevent increase in the number of individuals: with *O. brumata* it is rising mid-March maximum temperatures in the year before, with *E. defoliaria* it is rising minimum temperatures in October, with *C. pennaria* it is rising mid-December maximum temperatures in the previous year, with *E. aurantiaria* it is rising amount of precipitation in November, with *I. dimidiate* it is the early January minimum temperature the year before and rising late July minimum temperatures, with *S. nigropunctata* it is rising mid-November temperatures in the previous year, and with *P. comitata* it is an increasing amount of precipitation in April and rising mid-April minimum temperatures in the previous year. The number of individuals was high when there was more precipitation: for *C. pennaria* in February the previous year, for *I. dimidiate* in late March, for *E. pyraliata* in previous January, March, and late November.

4. I run the extended models with the estimates of the RegCM3.1 climate model for the reference period 1961-1991, then with its future estimates for the intervals 2021-2050 and 2071-2100. According to the estimates of the climate model for the 30-30 year periods, no significant change is expected in the number of individuals for *S. nigropuncta*. Only two of the species in the study, *E. pyraliata* and *O. brumata* are predicted to benefit from the future changes (in the case of the second, regarding the long-term average values). On the other hand, the climatic changes predicted by RegCM3.1 are expected to have an unfavourable impact on the number of individuals of *E. aurantiaria, E. defoliaria, I. dimidiata,* and *C. pennaria.* There might be a short-term drop in the number of *P. comitata*, however, a maximum level stagnation can also be prognosed for this species.

4. CONCLUSIONS AND RECOMMENDATIONS

Hungary lies on the border of the most vulnerable region in Europe, hit by both rising temperatures and shrinking precipitation levels. Climate changes will have a negative effect on the biodiversity of the country as well (EU Green Paper, 2007).

The climate of the Carpathian Basin is expected to become drier in future, with a direct impact on the insect population (Czúcz et al., 2007), since their life is seriously influenced by the outer world. Precipitation and temperature play a considerable role in the development of insects, because their life processes can be accelerated or delayed by these factors.

Research of the population dynamics of Geometridae (Lepidoptera) moths has huge significance in Hungary for forest and plant conservation, as of the winter moths species in the study belong to the insects that cause the largest area of total defoliation. The outbreak time and length varies for the species, consequently their flight is influenced in different ways by the constantly changing environmental impact.

- I was able to prove that there is significant negative correlation between the beginning and the length of the outbreak, i.e. the later the imago appears, the shorter the outbreak is. I could demonstrate that the beginnings and the lengths in the study period changed in a way that can be shown in a logistic curve. Furthermore, in the case of *O. brumata* I was able to establish a delay of the outbreak.
- To describe the population dynamics features of the univoltine Geometridae moths, I employed population dynamics modelling based on differential equations and indicator analysis (basic model). As a next step, using recorded daily records from the National Meteorology Service, I defined climatic indicators that, in accordance with the climatic demands required by the insects in their special phenological phase, show high correlation with the number of individuals. Linear combinations of these indicators were then implemented into the model as additive factors. Comparing the estimates of the basic model and of the one with the added climatic indicators, I could reveal that the models with climaticprovided more accurate results. Regarding winter moths, my results partly overlap with those by Leskó et al. (1998) and Szentkirályi et al. (1998) according to which the number of winter moth individuals increases in hot and dry years. In my study, I complemented this statement with the special effects of the different climatic factors. The development of the summer moths, which were examined side by side with the winter ones, depended mainly on the climatic factors in March and April. These non-pest species have not been examined from a population dynamics perspective, so most probably these are the first results about them. No worthwhile results due to Hungarian authors considering climatic factors can be found about *E. pyraliata, P. comitata, I. dimidiate* and *S. nigropucta* by. It was unequivocally proved by my research that there is significant correlation between the precipitation and the minimum/maximum temperatures and the outbreak, and the

various phonological phases, respectively. As a result of my work, the parameters that can have an impact on the development of the species can be defined with an accuracy of decades, approximately, which makes the information extremely useful in pest control.

- Estimates by the RegCM3.1 climate model yielded the following prognosis: According to the estimations of the population dynamical models run by the outputs of RegCM3.1 climate model for the 30-30 year periods, the number of individuals might increase in the short term for *O. brumata, C. pennaria, E. aurantiara* and *E. pyraliata*, while a drop is expected for *E. defoliaria* and *P. comitata*. In the long term the number of individuals is predicted to decrease for the *Erannis* species, while an increase is expected in the case of *E. pyraliata*. There is no significant change expected in the case of *S. nigropunctata, P. comitata* and *I. dimidiate*, consequently the population is not expected to be considerably influenced by the climate change in the long term. Of the species in the study only one will find the climate change beneficial, in other words, the future looks bright for *E. pyraliata*. On the contrary, the changes will bring bad news for the *E. aurantiaria*, and our model predicts hard times for the *C. pennaria*, too.

Our results might be important in plant protection prognosis and in pest control. However, a potential next step is to employ the models to investigate the population dynamics features of protected or rare moths or butterflies, pests, or insectsto reveal future changes.

5. PUBLICATIONS BY THE AUTHOR RELATED TO THE TOPIC OF THE DISSERTATION

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NO IMPACT FACTOR JOURNAL ARTICLE IN HUNGARIAN

Kúti Zs., Hirka A., Petrányi G., Szabóky Cs., Gimesi L., Hufnagel L., Ladányi M. (2010): A kis téliaraszoló (Operophtera brumata L.) aktivitásának modellezése abiotikus paraméterekkel. Agrárinformatika 1, 40-46.

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