



LUCAS: an original tool for landscape modelling[☆]

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Abstract

The aim of this paper is to present an original modelling tool for biogeographical systems. This software named LUCAS (LUcifer Cellular Automata Simulator) has been developed within the European programme LUCIFER (Land Use Change Interactions with Fire in MeditERRanean landscapes). LUCAS constitutes general software, based on coupling local dynamics described by a set of nonlinear ordinary differential equations with a cellular automaton spatial model. Various parameters related to the system considered can be chosen by the user. Numerous possibilities of LUCAS are illustrated through a real application regarding the catchment of a Polish river.

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Software availability

Name of the software: LUCAS

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Year first availability: December 2000

Hardware required: A platform to run MS Windows™ 32-bit applications

Software required: None

Program language: C++

Program size: 2MB

Availability and cost: at request

1. Introduction

One of the most important mathematical tools for modelling spatio-temporal systems are partial differential equations (PDEs), but many modellers in life sciences dislike such complex models. The weak connection between the very elegant theory of PDE's and the modelling of real systems is very often due to the unfamiliar jargon of the underlying sophisticated mathematics. The necessary prerequisite to employ such tools is good knowledge of functional analysis, operator and spectral theories, as well as real analysis. From an implementational point of view, the user must be familiar with variational approaches and must possess some knowledge of numerical analysis. So it is clear that PDEs will not provide useful insights or predictive evolutions for practitioners working in the field of very complex systems like e.g. in ecology. Obviously, PDEs may still offer an interesting framework for ideal studies on systems which are governed by such models.

Things become serious when the space dimension of the system functioning is greater than or equal to two. What is more, when a system is nonlinear with local interactions or specific behaviours (which is very frequently the case in ecological or biological systems), most of the mathematics falls down unless the modeller

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makes some simplifications or linear approximations of the system. The sum of these difficulties justifies approaches which make real complex systems more accessible for modelling and simulated predictions. In the case of landscape ecology (see Huston (1988)) there is an obvious environment heterogeneity, both in the underlying phenomena and in the pattern composition which makes the PDE approach extremely complex. For practically-oriented modellers other approaches can be more helpful for efficient predictive results.

When space, time and the phenomenon itself can be represented by discrete variables, an ideal approach in context is the framework of cellular automata (CAs) as presented by Toffoli and Margolus (1987); Wolfram (1994); Sipper (1997); Chopard and Droz (1998). Moreover, when we wish to take account of the local evolution, an additional model is needed. In this paper, we propose an approach based on coupling CA models with ordinary differential equations (ODEs). The resulting model presented here is obtained by combining the local evolution described by ODEs and a spatial spread phenomenon governed by a CA model.

This paper is organized as follows. In Section 2 we give a brief introduction to the CA approach. In Section 3 the main idea of the LUCAS software is presented and some details of the methodology are given. Section 4 illustrates the considered approach based on a real application regarding the catchment of a Polish river. A parameter estimation procedure is applied to improve the quality of the proposed model.

2. Problem statement and the proposed approach

Most real dynamical systems are intrinsically dependent on time and space. As such, they are said to be Distributed Parameter Systems (DPSs). The wide variety of these systems ranges from industrial processes to life sciences systems. The increasing attention paid to these problems naturally leads to important work on spatio-temporal processes.

The problem considered in the Lucifer (Land Use Change Interactions with Fire in Mediterranean landscapes) project is related to landscape fragmentation and changes in Mediterranean countries and their consequences on fire. The main task of our team involved in this research consists in finding an efficient approach to landscape modelling, which would take account of both spatial and temporal growths. The final product we have to provide should be quite easy for use and user-friendly even for non-specialists.

As for landscape modelling problems and various complex spatio-temporal systems, one can decouple modelling by considering on one hand the phenomena which are more specific to the time variable, and on the other hand, those related to space. Roughly speaking,

we can globally consider this decoupling by assimilating biological layers to time dynamics and geographical layers to space dynamics. In this context, we propose an approach which combines a continuous dynamics describing the growth phenomenon and a discrete dynamics for the spatial expansion. The local model is based on a set of ordinary differential equations (ODEs) which are in general nonlinear, and the distributed model is described by cellular automata (CAs). To begin with, let us give a brief description of CA models.

2.1. Cellular automata models

CAs are an idealization of real systems in which space, time and the physical quantities which determine the states are discrete. They were first introduced by Stanislaw Ulam and John von Neumann in the late 1940s to provide a formal framework for investigations of complex spatially extended systems (see Ulam, 1952; von Neuman, 1966). They are discrete dynamical systems which are often delineated as a counterpart to partial differential equations (PDEs), as they also demonstrate the capability to describe distributed systems.

They have been used to model many environmental processes (population genetics, interrelations between preys and predators in ecosystems, epidemic models, the effects of fire and dispersal on spatial patterns in forests), physical phenomena (fluid dynamics, reaction-diffusion, phase ordering, solidification of crystals, interfacial diffusion fronts) or engineering (geographical information systems, routing traffic in an urban area, image processing, cryptography, generating random numbers), see e.g. Chopard and Droz (1998); Crutchfield and Hanson (1999); Gaylord and Nishidate (1996); Sipper (1997); Toffoli and Margolus (1987); Weimar (1998); Wolfram (1994) and the references given therein.

Since the late 1980s, a lively interest in CA's has been observed as powerful computers have begun being widely available. Owing to their discrete nature, CAs are ideally suited for implementations. Various spatial processes in biology, such as population genetics, percolation, spread, etc., were already successfully simulated using CAs, see Green (1989); Greenberg and Hastings (1978) and Wolfram (1994). However, the research activity regarding CAs has been essentially focused on modelling and implementation problems so far. More work remains to be done in analyzing how CAs are capable of describing certain concepts which are intrinsically related to systems dynamics.

Formally, a CA is defined (see Wolfram (1994); Sipper (1997) and Chopard and Droz (1998) as the quadruple $A = (L, S, N, f)$, where

- L is a d -dimensional lattice of cells c which are arranged depending on the space dimension and cell shape. In the one-dimensional case, the cells are

ordered in a chain. For the two-dimensional case, one can tile the plane in different ways depending on the cell shape. Thus we may deal with a rectangular lattice for rectangular cells or a hexagonal lattice when the cells are hexagons.

- S is a finite set of values which may be taken by a cell. In particular, they can constitute a cyclic ring of power k .
- $N(c)$ is the set of cells c' which interact with c . The so-called *neighbourhood* of a cell c consists of the surrounding (adjacent) cells. For two-dimensional CAs, the most common neighbourhoods are presented in Fig. 1.
- f is a state transition function which defines the CA dynamics, i.e. we have

$$s_{t+1}(c) = f(s_t(N(c))) \quad (1)$$

where $s_t(c)$ and $s_t(N(c))$ denote respectively the state of cell c and that of its neighbourhood $N(c)$ at time t .

In order to study the global behaviour of a CA, it is often convenient to define the so-called CA configuration at time t which is formed of all cells' states at time t , denoted by s_t , and updated as follows:

$$s_{t+1} = F(s_t) \quad (2)$$

where F defines the global CA dynamics.

As usual for dynamic systems, initial and boundary conditions should also be specified. The most common choice is the periodic condition under which border sites may have neighbours on opposing borders. It happens, however, that the appropriate boundary condition consists in fixing the states of the boundary sites to a selected value, which is similar to Dirichlet boundary conditions for continuous systems. The initial condition means the initial CA configuration which may be taken in various forms as will be shown in what follows.

2.2. Coupling ODEs with Cas—hybrid models

The approach proposed in this paper aims at improving classical local models by taking into account the interactions between neighbouring individuals. We con-

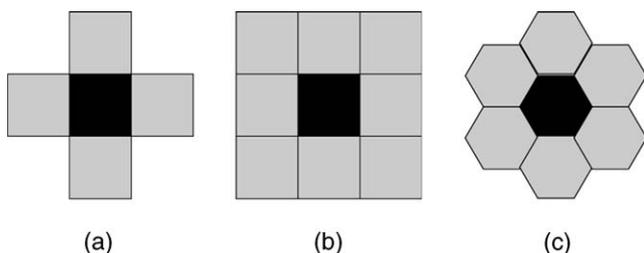


Fig. 1. Von Neumann (a), Moore (b) and uniform (c) neighbourhoods.

sider a two-dimensional CA lattice where each cell is occupied by an individual depending on the present species (e.g. a tree). Each cell can be in one of a finite number of possible states corresponding to real states of the individual (young, adult, etc.). The next state of each cell should result from a local evolution of its current state given by the ODE and the effect of the current states of a surrounding neighbourhood according to CA interacting rules.

It is not easy to introduce such a coupling process. The main problem is related to finding a convenient way to combine discrete CA states and continuous values derived from ODEs. In our studies, we compared two possibilities:

1. States are represented by integer values, which is compatible with the CA definition. Let \bar{s}_t denote the state of a given cell at time t . The first evaluation of the next state is determined by the ODE which computes a new value denoted by $\bar{s}_{1,t+1}$. This necessitates two conversions from real to integer values. The second evaluation is performed by the CA rule and $\bar{s}_{2,t+1}$ is thus obtained. The final result will be a linear combination of $\bar{s}_{1,t+1}$ and $\bar{s}_{2,t+1}$, cf. Fig. 2.
2. States may include real values and then the evaluation by the CA needs to be done via conversion from real to integer values. If the state value at time t is \bar{x}_t , the next state value will be a combination of $\bar{x}_{1,t+1}$ obtained by the CA and $\bar{x}_{2,t+1}$ computed by the ODE, cf. Fig. 3.

Note that here $\Gamma: x \in \mathbb{R} \rightarrow s \in S$ is the appropriate conversion operator and Σ is a linear combination of two discrete or real results corresponding to the first and the second scheme, respectively.

3. LUCAS as a tool for landscape modelling

LUCAS (LUCifer Cellular Automata Simulator) is software developed within the framework of the Lucifer project. The purpose of this program is to simulate and to predict spatial changes by means of CA models, lumped models described by a set of differential equations or coupled models which combine the two approaches. Even if LUCAS is a general package, in this section we focus our attention on the situation where the local dynamics is described by an extended GAP model (Shugart, 1984) and the distributed dynamics is governed by dispersal CA rules. These two models can be automatically generated in this program.

3.1. Patch dynamics

GAP models which were initially developed by Botkin in 1972 are based on the growth of individual trees.

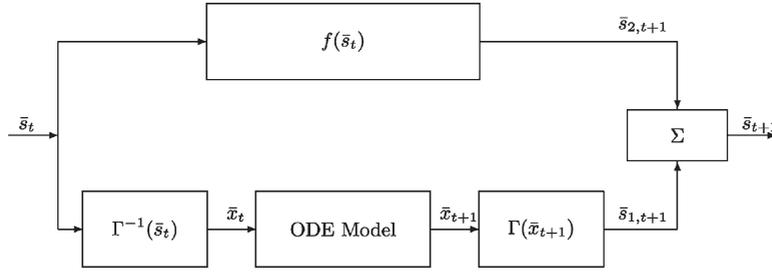


Fig. 2. Diagram of the coupled system with a discrete state vector.

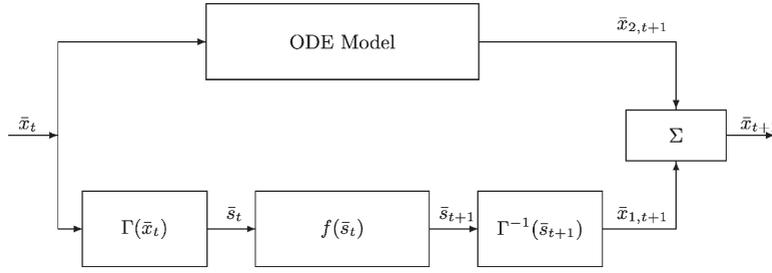


Fig. 3. Diagram of the coupled system with a continuous state vector.

The variable of interest in the GAP model is the diameter of each tree and its annual increase as a function of soil characteristics, competition rules governing the considered species and other climatic factors. It is described by a set of ODEs which determine the biomass evolution.

The heart of the considered model is the dynamics within the patch where we explore the possibility of finding various species. The patch size is related to pixels on a satellite map. The local model is mainly based on an extended GAP model, see Shugart (1984), which describes vegetation changes by periodically estimating the diameter increments of each tree on a prescribed plot. Landscape changes are then estimated using the behaviour observed from the plots.

The patch dynamics model will result from birth, growth and death analyses.

3.1.1. Birth process

Birth depends on both the species and their ability to give a good or a bad cone crop. Species that are very productive give new little shrubs every year, whereas less productive ones may have a cone crop every two or three years. If the years of good cone crops have been determined, the amount of new seedlings depends on the proportion of each species on the patch. The number of seedlings really established is affected by the probability of death and by a reduction factor due to light stress. The birth process will be described by the number of seeds $S_{y,i}$ during year y for species i which satisfies the following equation:

$$S_{y,i} = P_i S_{y-1,i} + S_{Tfi} - N_{germ,i} \tag{3}$$

where P_i stands for the probability of seeds to survive for at least one year, S_{Tfi} is the total number of alive seeds falling on the studied patch and $N_{germ,i}$ is given by

$$N_{germ,i} = P_{pm} \frac{S_{y,i}}{\sum_i S_{y,i}} r_{ALS_i} \tag{4}$$

where S_{pm} is the maximum number of possible seedlings including all species,

$$r_{ALS_i} = \exp\{-0.8L_{ai}\} \text{for shade intolerant species}$$

$$r_{ALS_i} = \exp\{-0.25L_{ai} - 1\} \text{for moderate shade tolerant species}$$

$$r_{ALS_i} = 1 - \exp\{-0.25L_{ai} - 0.2\} \text{for shade tolerant species}$$

(5)

3.1.2. The growth process

Each tree is described by its diameter D measured at height $H_0 = 1.37$ m, which is related to the tree height H through the formula

$$H = H_0 + b_2 D - b_3 D^2 \tag{6}$$

where b_2 and b_3 are two parameters determining the tree form,

$$b_2 = 2 \frac{H_{max} - H_0}{D_{max}} \tag{7}$$

$$b_3 = 2 \frac{H_{max} - H_0}{D_{max}^2} \tag{8}$$

All the involved coefficients which constitute some characteristic parameters of the considered species will be summarized in a table given below.

The generated growth model depends on the species which is classified as short vegetation with $H_{max} < 3$ m or normal vegetation when $H_{max} > 1$ m. The corresponding two differential equations are given by

$$\frac{dD}{dt} = r_{AL} r_N r_w r_{Degd} \frac{G[1-DH/(D_{max}H_{max})]}{3b_2-4b_3D} \quad (9)$$

for short vegetation and

$$\frac{dD}{dt} = r_{AL} r_N r_w r_{Degd} \frac{GD[1-DH/(D_{max}H_{max})]}{2H_1 + 3b_2D-4b_3D^2} \quad (10)$$

for normal vegetation. Here

$$G = f(D_{max}, H_{max}, Age_{max}) \quad (11)$$

is a characteristic parameter of species, which has to be computed from the formula

$$G = \frac{4H_{max}}{A_{ge_{max}}} \left[n[2(2D_{max}-1)] + \frac{\alpha}{2} \ln \left(\frac{9/4 + \alpha/2}{4D_{max}^2 + 2\alpha D_{max} - \alpha} \right) \right. \\ \left. - \frac{\alpha + \alpha^2/2}{\sqrt{\alpha^2 + 4\alpha}} \ln \left[\frac{(3 + \alpha - \sqrt{\alpha^2 + 4\alpha})(4D_{max} + \alpha + \sqrt{\alpha^2 + 4\alpha})}{(3 + \alpha + \sqrt{\alpha^2 + 4\alpha})(4D + \alpha - \sqrt{\alpha^2 + 4\alpha})} \right] \right] \quad (12)$$

where $\alpha = 1 - H_0/H_{max}$.

Reduction factors r_{AL} , r_N , r_w , r_{Degd} which are introduced according to the patch conditions (topography, soil, weather, shade tolerance, etc.), have to be specified, too. This is accomplished as follows:

- The light effect r_{AL} is given by

$$r_{AL} = 1 - e^{-4.64(AL-0.05)} \quad (13)$$

for shade tolerant species and

$$r_{AL} = 2.24 [1 - e^{-1.136(AL-0.08)}] \quad (14)$$

for shade intolerant species, where $AL = \phi e^{-0.25\Sigma Lai}$ is the light available for a given class of trees, ΣLai is the shading leaf area index defined as the sum of the leaf areas of all higher trees on the plot (heights obtained from eq. (6) per m²) and ϕ is assumed to be the annual insolation (usually $\phi = 1$).

- The crowding effect r_N is given by

$$r_N = 1 - \frac{B}{B_{max}} \quad (15)$$

where B and B_{max} are the actual and maximum reachable biomasses, respectively.

- The water stress r_w is given by

$$r_w = 1 - [(1 - A_{pr}) / (1 - W_{soi})]^2 \quad (16)$$

where $0 \leq A_{pr} \leq 1$ is a dimensionless coefficient given by $A_{pr} = \frac{A_{ET}}{P_{ET}}$, W_{soi} being the lower limit of the tolerance for species i .

- The temperature reduction factor r_{Degd} is given by

$$r_{Degd} = \frac{(D_5 - D_{5min,i})(2D_{5opt,i} - D_{5min,i} - D_5)}{(D_{5min,i} - D_{5opt,i})^2} \quad (17)$$

3.1.3. Death process

Death may be due to a stress event or the fact that the trees have reached their maximum age. The mortality may be mainly provided by considering random or stress mortalities and will be described by the probability to get dead trees.

Let P_{sr} be the annual probability to survive for random mortality, and P_{ss} the annual probability to survive for stress mortality. Thus we have the following relations:

$$P_{sr} = (0.01)^{1/Age_{max}} \quad (18)$$

$$P_{ss}(y_s) = 0.82 P_{ss}(y_{s-1}) \quad (19)$$

where y_s is the number of stressful years. It is determined via comparison of the plant annual growth ΔD and the threshold value $T_{inc}(i)$. We have a stressful year for big trees if $\Delta D < T_{inc}(i)$. But for shrubs there is a stressful year provided that $\Delta D / \Delta D_{max} < T_{inc}(i)$.

Actual evapotranspiration	A_{ET}
Potential evapotranspiration	P_{ET}
Degree day of the site	D_5
Minimum degree day bearable by species i	$D_{5min,i}$
Optimum degree day bearable by species i	$D_{5opt,i}$
Maximum diameter of the tree	D_{max}
Maximum height of the tree	H_{max}
Initial diameter breast height of the tree	H_0
Maximum age of the tree	Age_{max}
Breast height	H_1

3.2. Spatial dynamics

In this section, we are concerned with the description of the seed dispersal phenomenon by means of a distributed model. The proposed approach is based on CAs which constitute a candidate class to model such processes.

3.2.1. Space dispersal modelling

The effect of the seed dispersal process is to involve interactions between patches. The considered CA is based on the following parameters:

1. The **lattice** is regular and composed of square cells which represent patches of a certain size being an adjustable parameter depending on the considered application.
2. The **neighbourhood** is a Moore one, so it is a symmetric neighbourhood. An averaged wind direction can be modelled by considering other types of neighbourhood.

3. The **state set** is given by $S = \{1, 2, 3\}$ where the state values are chosen to represent the vegetation on a cell at time t in the following manner:
- State 1 characterizes a vacant cell.
 - State 2 characterizes a cell occupied by vegetation that cannot produce seedlings.
 - State 3 characterizes a cell occupied by vegetation that produces seedlings.
4. The **program** is based on the state evolution rules defined for any cell denoted by c_{ij} as

*state 1 \rightarrow {state 2 if it has a neighbour at state 3, state 1 if not.
 *state 2 \rightarrow state 2
 *state 3 \rightarrow state 3

and each cell c_{ij} receives 5% of the N seed from the neighbours in state 3, where N seed is the number of new seedlings appearing in any cell c_{ij} at time t , either by local production or by the neighbourhood influence.

3.2.2. Remark 3.1

1. The number of seeds provided to the neighbours is determined according to McCaughey et al. (1985) and Tomback (1995) as a seed dispersal probability.
2. It is supposed that the entire studied domain can be colonized by the species.
3. The gap model uses a fixed year time step. The CA uses a variable time step equal to 1, 2, 3 or more years according to the years of good cone crops.
4. The values of all the involved coefficients which are necessary for numerical simulations are available from the literature for the most representative species in the studied Mediterranean areas.

4. Implementation of LUCAS for the Ratanica catchment

Since the proposed model operates on a precise description of the trees, it is a good idea to validate it on a small part of an ecosystem. A good example for this is the Ratanica catchment, which was thoroughly studied in the 1990s (see Grodzinska and Laskowski, 1996). Lucas is currently under development for other real situations in Spain. Its implementation and the associated simulation results will be illustrated in El Jai et al. (submitted). Ecological Modelling. A new approach for landscape modelling and interaction with fire.

4.1. Characteristics of the Ratanica catchment

The Ratanica is a river whose catchment is located in Southern Poland (49°51'N, 20°02'E), 40 km south of the city of Cracow and in the vicinity of a big water reservoir providing the city with drinking water. The entire catchment covers 241.5 ha. The vegetation of the

catchment is typical of the Carpathian Foothills. Its upper part is covered with forests, while the lower one with meadowland fields. The forests are of anthropogenic character. Coniferous species (*pinus sylvestris* and *larix decidua*) are dominant. The main deciduous tree is beech (*Fagus sylvatica*).

Beech-pine and pine-beech woods dominate in the catchment. The age of trees ranges from 40 to 80 years, the oldest classes being rarely found. The results of dendrometric studies in the Ratanica catchment indicate a large potential productivity. The most dynamic tree species in this region is beech. Its expansion and regression of Scots pine and larch might have been caused by changes in the forest management and increased atmospheric input of nitrogen.

In order to compare the behaviour of our model with nature, initial and final values for the volume occupied by the trees (i.e. the biomass volume) were taken (the results for the middle values are not included here due to limited space). For this comparison, the following information was used: soil configuration (only for the initial condition), species composition of tree stands and large timber volume measurements for the lattice composed of square patches with sizes 200×200 m, cf. Fig. 4. Each patch is represented by a number from 1 to 32. This makes a possibility of comparison only for patches (not for individual trees, as this would be ideal but very hard to interpret owing to simplification and generalization of the GAP model).

4.2. Simulation results

Due to the lack of sufficient information about dominant species of the Ratanica catchment, in order to start the simulation process (the parameters suitable for Polish species have not yet been described), we need to estimate proper values based on known similar Mediterranean species and real data collected by the foresters.

The values of biomass are only known for three consecutive years, cf. Fig. 5, so for estimation of GAP model parameters we can select 90 pairs per species.

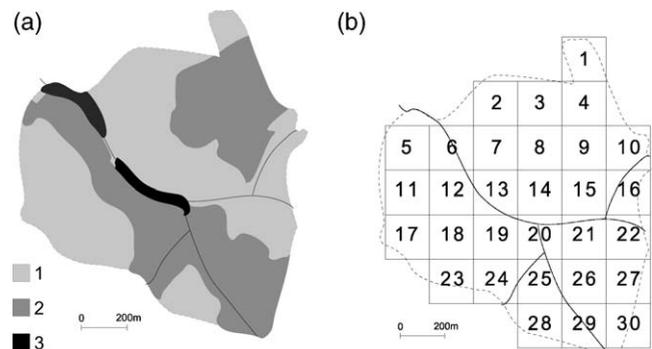


Fig. 4. Scheme of the Ratanica catchment, Soils (a) and Patch division (b).

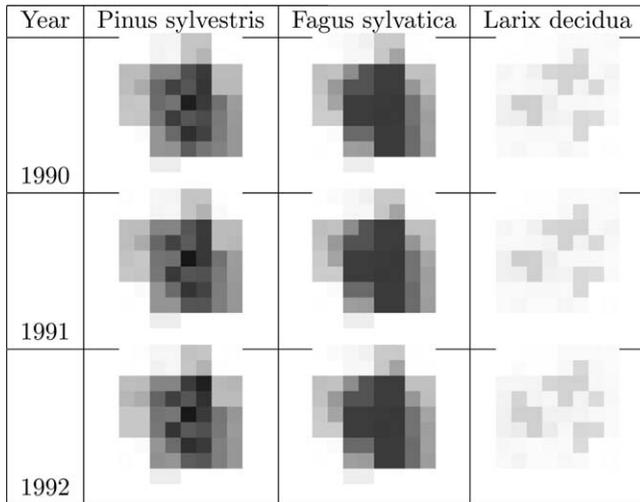


Fig. 5. Three-year data configuration for each species.

Simulation using our CA with the lattice of 60×70 cells was stopped after the period of one and two years. The colour gradations represent three states of the CA which corresponds to different values of biomass for each species.

Fig. 6 presents the initial biomass value for each species at each patch.

After two years, the simulation results provide very promising values, cf. Fig. 7. The maximum error level is 1%. This result is obtained by the parameter estimation process. It is possible that comparison of simulation for longer periods with real data may generate larger errors. For the first two species, the errors are less than 0.2%.

For the third one which is dominant on few patches in the Ratanica area, only a few data have been estimated and therefore errors are more important.

In Fig. 8 we present the global evolution of the three species. The changes are not very significant in two years. With the improved model, we can observe the landscape evolution for the following years in order to predict the general tendency. Unfortunately, we do not have the possibility of comparing those results with a real evolution because of the unavailability of additional data in the literature.

It can be concluded that the proposed model is fit to predict the growth tendency and general biomass states. Some errors may result from incorrectly tuned parameters of the gap model: we verify a model based on Polish species which are not so well documented in the gap context. Additionally, our model does not take into account human and nature’s intervention (fire, cutting trees, pollution, etc.)

Appendix A. Software principles

The present section concerns the main characteristics of LUCAS (LUcifer Cellular Automata Simulator). The program operates in the Windows environment (Win98 or WinNT) and is powerful but very easy to use except for some specific situations when a few adjustments may be needed to do by users. It produces the prediction of what a landscape would be in the future taking into account fire.

The main LUCAS window presents a menu with items

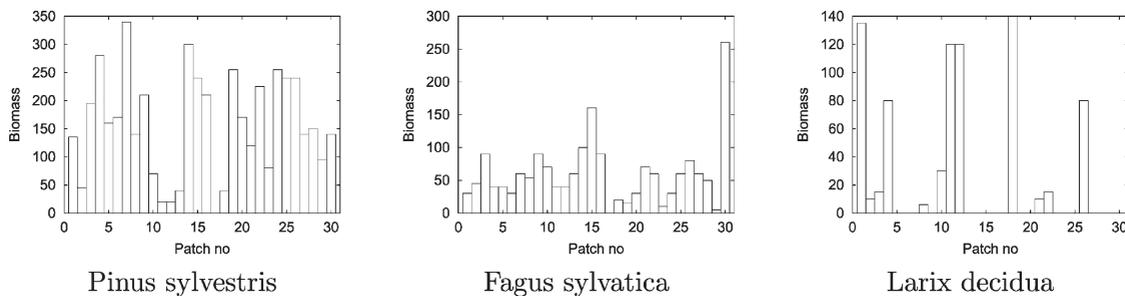


Fig. 6. Initial conditions for the biomass.

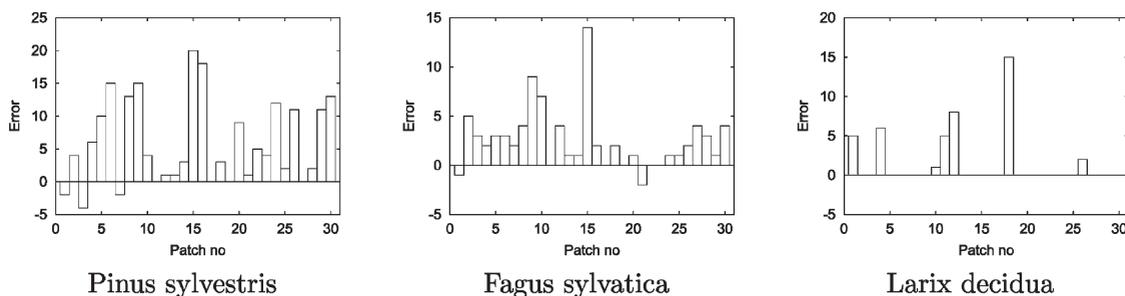


Fig. 7. Error evaluation for parameter estimation.

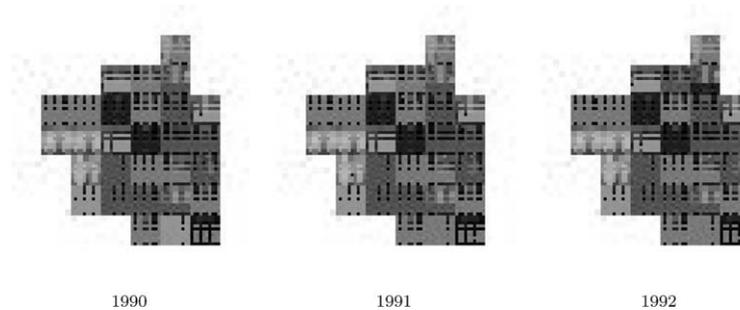


Fig. 8. Landscape evolution.

Properties, *View* and *About*. The first menu *Properties* allows us to enter the main features of the model while the *View* menu leads you to various graphs.

- Within the *Properties* menu the main modelling work is to be done: You have to give all the parameters of the experiment. When you click on *Properties*, you get in a sub-window with items *Species*, *Patch dynamics*, *CA dynamics* and *Additional settings*. The user has to go through these four submenus.

1.1. Clicking on the **Species** menu will bring you to the choice of the species and the associated soil and climate conditions within the patch. For the given species (the most representative in Mediterranean areas), you can validate the given values or modify some of the values or also enter the coefficient values of your species to make the model complete. In simulations you may consider up to ten species. For a higher number you will probably need a very powerful computer.

1.2. The **patch dynamics** menu will allow you to generate the evolution dynamics of the selected species within the patch. For each species the dynamics is described by a first-order ODE. For non-professional users an extended gap model is given but it can be modified or replaced by any model of your choice.

- The applied numerical method for solving the generated first-order differential equations in this program is of the Runge-Kutta type. You have then to decide for the numerical integration of the patch dynamics about.

1.2.1.1. the CA number of states. This means that for your species you will visualize, in the landscape, only this number of states (for example young, adult and old are three possible states).

1.2.1.2. the landscape time scale ΔT . The evolution of the landscape will be viewed every $k\Delta T$ for $k = 1, 2, \dots$. If $\Delta T = 1$, then the landscape evolution will be viewed every year.

1.2.1.3. the RK4 step is the local time step in the patch dynamics resolution. The larger it is, the more accurate the results will be, but the time of computations will be also higher.

- In front of each equation line a coefficient to be given by the user in percents is required. It offers the user a possibility to take account of any external phenomenon which makes a species more or less present (particular soil conditions, pollution phenomenon, ...).

1.3. The **CA dynamics** will describe the space dynamics of the landscape. The model is based on a CA for which one has first to determine the neighbourhood which defines interactions between patches. You have to fix both the size and shape. The transition function which governs the dynamics of CAs is to be determined by the user for each species. For non-experts a dispersal rule is automatically generated as described in the previous sections. We have chosen this type of dynamics because dispersal is the most reasonable way of space evolution.

1.4. In the **additional settings** menu you have to decide for the initial data given as a bitmap file. For that purpose you can use a given file (“read from file”) or create a new bitmap file (e.g. via Microsoft Paint). Then the user has to decide for the simulation colours in the landscape evolution. For that purpose, you have to click on each state of every species and associate your selected colour. You also have the possibility of choosing two weighting coefficients depending on how you wish to combine local evolution with space pressure. If you have no idea for that, the choice gives the same value for both.

- The *view* menu allows you to:
 - 2.1. Zoom in or out of the landscape map, modify the simulation speed.
 - 2.2. Save the state of the landscape as a bitmap or a postscript file for presentation, for printing or adding the figure in a paper.
 - 2.3. Visualize the graph of the biomass (or fire severity) evolution on a selected cell or over all

the landscape. In this case, you have to decide for the period you are interested in and the species you wish to visualize.

- The *About* menu gives indications on LUCAS authors.

Remark 4.1

You have the possibility of adding fire in the landscape. This is to be done “by hand”. As regards the landscape scale with a time step of 1 year, the fire duration is very prompt. Thus we suggest for adding a fire effect to stop the simulation and to burn patches by clicking on them. You have the possibility of deciding for fire severity (in percents). This means that the biomass on the burned patches will be reduced by the chosen percentage. Afterwards, you click on the desired patches and run your simulation. The first step will give the state of the landscape after one year. Obviously, you will get young vegetation over all the burned patches.

System requirements

- The LUCAS program can run on a Personal Computer with Intel 486 or a higher processor. In this case, Pentium II 333 MHz is recommended.
- This application requires a minimum of 32 MB of RAM and 50 MB free hard disk space because of the huge amounts of generated data at each simulation step.
- The Lucas source is written in C++ language.

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