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ForestMAS – A single tree based secondary succession model employing Ellenberg indicator values

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ABSTRACT

Over recent decades farmland abandonment has affected large areas of the landscape. To better predict the changes associated with this process, we developed a secondary succession model based on Ellenberg indicator values describing the ecological niche of a tree along environmental gradients. These values are compared with local ecological factors dependent on terrain conditions. The terrain is represented by a Digital Terrain Model, where the local conditions are represented by a light availability model, climate data, soil properties, and a combination of a water flow model and average annual rainfall data. Each tree in our model is associated with its immediate circular ecological neighbourhood and is treated individually from the seedling stage through to its decay. Each year, tree heights, actual vigour, and neighbourhood radii were calculated. When two radii intersected, the vigour of both trees was compared. The weaker of the two became dominated, leading to stress-related mortality. When a tree reached the adult stage, it produced seeds that established new seedlings that competed for light and nutrition. To start the simulation, the initial amount of seed was planted on bare ground. It was possible to monitor the succession phases either visually or statistically. 3D tree models were used to visualize a tree at any age, generating realistic landscape images useful for demonstrating long-term changes in the cultural landscape to non-experts. The results were compared with those from previous field studies in various areas of Slovenia. Apart from predicting landscape changes after farmland abandonment, the model can be used for forecasting the regeneration process after clearcutting or natural disasters.

1. Introduction

In the late 1940s, entire villages were abandoned in Slovenia. The affected regions became economically unimportant and have remained so. In recent decades a similar process has been occurring in Slovenia and in the Balkans. It is occurring at a much slower rate and for different reasons, but with similar consequences. Farmland with higher production costs is being abandoned and is slowly being colonized by forest. Since this process is gradual, people are mostly unaware of it. To prevent the stagnation of the affected regions, there is a need for appropriate tools, firstly to point out the necessity for new policies by highlighting the long-term changes in the cultural landscape, and secondly to support the decision making process. One possibility to better understand the process would be the use of forest growth simulators, gap models, or similar tools. Thorough overviews of these simulators are given in Liu and Ashton (1995), Bugmann (2001), and Pretzsch et al. (2008). Although these simulators are very impressive, they were created to support decisions aligned with forest management and are mainly focused on the annual biomass and volume increment of existing stands. Growth models are based on the long-term measurements of increments in tree diameters and heights taken at predefined time intervals, usually every five years. The oldest measurements used in the SILVA growth model (Pretzsch et al., 2002), for example, even date all the way back to 1870. Because these measurements were used to predict timber production in particular stands, only economically important tree species, such as *Picea abies* (L.) H. Karst., *Abies alba* Mill., *Pinus sylvestris* L., *Fagus sylvatica* L., and *Quercus petraea* (Mattuschka) Liebl., were included. Other trees of little economic value, but of high ecological importance, such as *Betula pendula* Roth, *Salix caprea* L., *Carpinus betulus* L., and *Alnus glutinosa* (L.) Gaertn., were left out. From a computational point of view, forest gap models such as JABOWA (Botkin et al., 1972), ForClim (Bugmann, 1996), and many others (Bugmann, 2001) are very interesting since the forest is abstracted as a

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composite of many small patches of land mostly without any interaction among them. These models are therefore especially suitable for parallel computing on graphics processing units with the possibility of considerable speedups (Garland et al., 2008); however, an important drawback in virtually all of them is that the early stages of succession cannot be simulated because the height of trees must be 2 m or higher (Bugmann, 2001). Another approach is presented in the work of Pueyo and Beguería (2007), who developed a Markov logistic model for predicting the rate of secondary succession. In the model, the land can be covered by crops, shrubs, or different types of local forest according to its elevation, but detailed forest composition and water and nutrient availability due to local topographical conditions play only a secondary role. Another problem is that transition probabilities in the model are obtained from observations of Mediterranean mountainous areas that are quite specific and not general enough for our purposes. An important problem in existing forest simulators is that their results are primarily aimed at forestry experts and are thus difficult for the general public to understand. In order for the statistical results to achieve greater impact, the visualization of changes in the cultural landscape should be implemented as well.

We therefore developed ForestMAS, a new forest simulation model for secondary succession in which all of the important species are taken into consideration. Since obtaining reliable quantitative data on autecology proved impossible for so many trees over a short time period, indicator values as proposed by Ellenberg et al. (1992) were used. The Ellenberg system has already been confirmed by several authors (e.g., Persson, 1981; van der Maarel, 1993; Diekmann and Dupré, 1997; Koerner et al., 1997; Diekmann, 2003) and has also been partially used in SILVA (Pretzsch et al., 2002) and ForClim (Bugmann, 1996). The Ellenberg indicator value (EIV) for tree light demand was used in SILVA and ForClim, and an additional EIV for temperature was employed in ForClim. In order to fully describe plant needs, additional indicator values (soil moisture, acidity, and nitrogen/nutrients requirements) were introduced in ForestMAS.

A key part of ForestMAS is the visualization of landscape changes during secondary succession. There are a number of algorithms available for this purpose in the literature, e.g., Weber and Penn (1995), Prusinkiewicz and Lindenmayer (1996), and Pałubicki et al. (2009). Plant visualization algorithms generally involve a large number of parameter values and are computationally demanding. ForestMAS makes use of the faster Holton model (Holton, 1994), which works equally well for both deciduous and coniferous trees and can generate high precision tree geometric models at any tree age. We used the Holton model to generate a series of tree images at different ages, which served as textures that were mapped on three intersecting planes and thus gave the impression of a 3D tree at any camera angle. This is acceptable since the trees are part of the landscape images and with the use of textures we obtain the same quality of tree images in much less time.

With the ability to produce realistic landscape images, ForestMAS enables the observation of any long-term landscape changes. If the area is small enough (<10 ha), these changes can be seen in a real time animation, but for larger areas only static images can be generated.

2. Materials and methods

2.1. Ellenberg indicator values

Reliable data describing plant requirements are necessary for developing a consistent secondary succession model. Reliable long-term measurements exist for economically important tree species, but these make up only a small number of the species that are important for secondary succession. Such measurements do not exist for pioneer species that are extremely important for secondary succession but have little or no economic value, such as *Betula pendula* and *Salix caprea* (Connell and Slatyer, 1997; Kimmins, 2004). One solution to this problem lies in the Central European plant classification system proposed by Ellenberg et al. (1992). Ellenberg indicator values (EIVs) provide simple ordinal classes where plants are ranked according to their requirements for soil acidity, nutrients, soil humidity, continentality, temperature, soil salt content, and light. The indicators for land plants contain values on a 10-point scale, where the last point, denoted by the value *x*, indicates that the given indicator has no influence. Each plant in the Ellenberg classification is thus described by a set of seven numbers expressing the average plant requirements along seven fundamental gradients. In order to employ EIVs in ForestMAS, the following steps were necessary:

Table 1
Scale for the Ellenberg soil acidity (reaction) indicator (E_R).

Value	pH range	Meaning
1	≤4.4	Extremely acidic
2	4.5–5.0	Very strongly acidic
3	5.1–5.5	Strongly acidic
4	5.6–6.0	Moderately acidic
5	6.1–6.5	Slightly acidic
6	6.6–7.3	Neutral
7	7.4–7.8	Slightly alkaline
8	7.9–8.4	Moderately alkaline
9	≥8.5	Strongly alkaline
x (10)		Indifferent

(1) *Substituting the mostly descriptive EIV boundaries with solid values* – this step was necessary in order to adapt the discrete EIVs to interpretable and measurable values for site quality. The indicator for light, the most often used EIV, classified plants on a scale between light demanding and shade tolerant. Therefore, the main criterion was the obstruction of sunlight. The sites that received direct sunlight all day were given the maximum value based on which the scale is adapted. In the case of soil acidity, a different approach was used. Table 1 shows an example of the quantitative borders for the soil acidity EIV proposed by the Natural Resource Conservation Service of the US Department of Agriculture (Soil Survey Division Staff, 1993).

The temperature EIV in the Ellenberg classification system is a substitution for the annual sum of degree-days used in JABOWA (Botkin et al., 1972) and algorithms used in the majority of later gap models to define the effect of temperature on tree growth. It is strongly correlated with the terrain elevation and, with the exception of the last two points (8 and 9), is bound to altitudinal vegetation zones. The last two points on the EIV temperature scale designate very hot climate typical for sub-Mediterranean and Mediterranean areas. The highest average annual temperatures in Slovenia exceed 12 °C in only a few coastal regions, and are mostly between 10 and 12 °C, which has also been the case in the last 10 years for all lower areas of the country. Therefore, in ForestMAS the temperature borders depend entirely on the terrain elevation with point 1 in areas with elevation higher than 1650 m and point 9 in areas lower than 200 m. In order to apply the nutrient EIV, we took into account the work of Hawkes et al. (1997), who used Ellenberg EIVs for acidity, moisture, and nutrients to assess soil quality in British forests. They measured the total amount of elements important for plant growth (N, K, Ca, C, Mg, and P) and showed that the quantities of total N, C, and P were not important for separating sites with different EIV for nutrients, which was consistent with the previous work of Khanna and Ulrich (1984), who noted that the N status of plantation soils was usually assessed by the rate of mineralization. Instead, they proposed a combination of the