A Spatially Explicit and Temporal Dynamic simulation Model of Forested Landscape Ecosystems

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Abstract The ecological processes acting within a forest and the consequent dynamics create landscape patterns. The precise nature of these patterns will vary depending upon the space/time scale of analysis. An individual tree-based model was developed to simulate forest patterns defined in terms of age and composition resulting from the interactions among seven species. A series of 2-dimensional lattice objects were created to represent the environmental conditions in which the trees live. A 2-dimensional discrete lattice also served as the spatial location for the trees. The forest simulation model was developed with object-oriented modelling and programming technology using the Santa Fe Institute's Swarm simulation environment, which was developed as an interdisciplinary standard platform for agent-based simulation modeling. The basic assumption underlying our use of this model is that the forested landscape can be viewed as a self-organized complex system, in which individual micro-level interactions lead to emergent macro-level phenomena, which in turn feed back to affect micro-level actions. Also we assume that key interactions among individuals and their environment are dynamic and non-linear. Spatial and temporal dynamics were simulated by modelling interactions among the individual trees as agents, and between these tree agents and their physical environment. The model incorporates the effects of mortality, regeneration processes, and fire. Simulations were run using a yearly time step over a period of hundreds of years. The results support the view that individual-based simulation models, and the object-oriented modelling approach generally, are very useful tools for exploring the dynamic interactions between ecological processes and landscape patterns.

1.1 Introduction

Ecosystems involve interactions between hierarchically structured constituent components, and are increasingly viewed as self-organized complex adaptive system. A complex system is not governed solely by top-down rules, though there are usually some global constraints on each individual system component. In addition to these global constraints, the interactions of individuals is a key source of higher-level system behavior. These interactions are hypothesized to produce patterned, ordered structures with recognizable dynamics.

If an ecosystem is viewed as a complex system, it means that small-scale interactions can produce large scale structures. These in turn provide a larger scale context within which elements function, and which in turn can modify activity at the smaller scale. Therefore, somewhat counter-intuitively, large scale phenomena can be explained, and indeed derived, from modelling interactions among individuals at a smaller scale (see Kauffman, 1995).

Ecosystems therefore can be seen as representing a high level of ecological integration, with emergent properties, and feedback between small and large scale phenomena. They comprise interactions between components that have an individual identity and a specific location. These elements exchange energy and material in a non-linear and dynamic way. Change in the system therefore derives partly from external effects, but also from self-generated dynamics. The biological entities are capable of modifying their local environment, and adpating to changing environmental conditions. These interactions result in variation in the spatial and temporal composition of species across the landscape, or, what is termed, vegetation succession (for further discussion of scale, hierarchy and ecology, see Allen and Koestra 1992).

There are at least two ways to approach the problem of simulating ecosystem pattern and process as defined above.

The first involves a traditional top-down analytic approach, which uses aggregate parameters, and describes the higher hierarchical levels of a system by concentrating on the larger scaled factors controlling ecosystem dynamics. Models developed with this approach basically break the whole system into its constituent components, and apply analytic approaches to explore the functional relations of these components. These are then combined them to form an overall understanding of the system. The models developed with ordinary differential equations (ODE) or partial differential equations (PDE) are typical examples. These models have advantages in the projection of certain aspects of the system's dynamic behavior, and still have a wide range of use in many theoretical and practical application area.

A major disadvantage of this modelling approach is that it can suppress the influence of individual identifies within the system. For example, the effects of small differences between individuals in an ecosystem could lead to unpredictably larger difference at a high level of organization. Also, as noted above, the local effects of interactions could result in pattern creation which in turn influences ecological process related to germination, plant growth and fire.

We hypothesize that a bottom-up synthetic approach based on complex system theory, overcomes many of these disadvantage. This approach proposed that the critical step towards understanding ecosystem pattern and process is to build a holistic picture of the ecosystem by studying the collective behavior of individual agents. Examples of such agent-based models (ABM) or individual-based models (IBM) are given by Heibeler (1994) and Huston (1991). ABM or IBM models try to approximate the real ecosystem with a certain degree of abstraction. The agent is what we are interested to experiment with in our simulation, and the environment is where the agents live. The simulation is achieved by assigning each of the individuals a role to play, and establishing the interactions among these individuals and the individuals with their environment. So the models developed with ABM or IBM are more informative and comprehensive than the models developed with ODE or PDE. ABM or IBM when used in ecosystem modelling and simulation can provide the power to explore how spatial and temporal patterns might arise in real world heterogeneous landscapes, and therefore is useful to natural resource management problems.

1.2 Basic design of the simulation model

The ABM or IBM approach provides a useful framework for testing theories or hypotheses about ecosystem pattern and process. In this study, we use this general approach to study the spatial and temporal dynamics of a forested landscape ecosystem specifically in terms of species diversity and age structure.

1.2.1 The Individual tree as the basic building block in the landscape ecosystem model.

The critical step in applying agent-based modelling is to define: the constitutional parts of the landscape ecosystem; the basic agents and their roles in ecosystem dynamics; how they fit together; what kind of interactions occur among them; and which emergent behaviors we want to observe from these interactions.

In the wet sclerophyll Eucalypt forests of southern Tasmania, the species diversity, age structure, and their spatial and temporal dynamics are the primary focus of interest. We assumed that species diversity and age structure are emergent properties of the interactions of the individual trees, and of the individual tree with their environment. Therefore the individual tree is identified as the basic agent and key player in the forested landscape ecosystem.

1.2.2 Defining the tree's environment using a 2-dimensional grid-based digital representation of the terrain and related raster objects

The environment that the tree agents live in is defined by the distribution and availability of the primary environmental resources that drive the response of photosynthesizing plants. We adopted here an explicit framework which selects attributes at meso and topo scales that define the distribution and availability of heat, light, water and mineral nutrients (Mackey 1996).

We defined series of 2-dimenstional raster objects to represent the selected environmental resources spatial configuration in a similar manner to most raster-based GIS.

A digital representation of the terrain, ie. a digital elevation model (DEM), was created to factor in the effects of elevation and topography. A grid-based topographic analysis program, TAPES (Topographic Analysis Package for Environment Study (Moore, 1993), was used to generate gridded estimates of terrain attributes that are correlated with the distribution of primary environmental resources. For example, use was made of the topographic wetness index from TAPES (a ratio of specific catchment area to slope angle) to estimate surface water flows.

The DEM-based environmental models captured the spatial distribution of meso-scaled climate as well as the effects of local topography on soil water etc. These meso- and topo-scaled variables in turn place constraints on the probability of a species occurrence in the landscape, and influence forest productivity, fuel accumulation and decomposition, and consequently fire intensities.

Spatially explicit modelling was achieve through creating a grid-based 2-demensional lattice object. This object serves as a location holder for each of the individual tree agents, and therefore provides a way to implement the interactions among the individual trees and individual trees with their environment.

1.2.3 Simulating the regeneration process

In a forest ecosystem, strong competition occurs when the environmental resources become limiting for the growth and reproduction of a species. It was therefore assumed that competition for available resources among species on the site controls species diversity in the landscape. The competitive individuals will have more opportunity to reproduce themselves, while other individuals will therefore not have the chance to reproduce themselves and finally die out during the successive years. As time passes, certain patterns of species diversity will emerge at the landscape level.

The regeneration process and competition effects were modelled by taking into account the availability, periodicity and durability of seed, degree of shade tolerance of the species (ie. the degree to which it can regenerate under shade), and site availability (ie. of suitable space for the seed to germinate and grow).

1.2.4 Modelling the effects of fire on age structure and species diversity

Fire has been recognized as a very important ecological process in Eucalypt forests in Australia (Gill, 1975) with the intensity and frequency of fires playing a significant role in modifying age structures and species diversity.

In the model, the occurrence of fire is randomly generated with a empirically derived probability distribution. The intensity of the fire is a function of climatic condition, described with McArthur's fire danger index (FDI) (McArthur, 1967), the fuel load in the forest stand, and topographic effects.

1.3 The role of object-oriented modelling and programming technology in building dynamic landscape simulation models.

In order to build a computer model, we treated the tree agents and their environment as the target objects. By doing so we could map these landscape objects into the equivalent counterparts of computational objects within the framework of object-oriented programming. We contend that object-oriented modelling and programming has an important role to play in simulating landscape ecosystem pattern and process.

Object-oriented modelling and programming aims to deal with the modularization of a system (for information about object-oriented modelling and programming, see NeXT Inc document). It conceptualized a system as a collection of many objects (modules or mini systems) which are hierarchically organized, and combines these objects into structured forms through "is a" or "part of" relationship. This represents a conceptual abstraction of a real system through certain functional relationships. The object has its own properties (denoted with variables in computer program) and behaviors (achieved through computational representation of functions). In our model's context, this means an object is capable of behaving so at to maximize its 'well-being', and also is capable of interacting with others. The behavior required from an object by other objects can be triggered by invoking one of the implemented functions. The overall behavior of the system is achieved through interactions of the objects that send and receive messages from each other. So as a group these objects can accomplish behaviors more dynamic and complex than each of them individually.

Since the basic concepts of object-oriented modelling and programming are very similar to how we envisage the hierarchical organization of ecological objects, it provides a intuitively appealing way to approach the problem of modelling pattern and process in an ecosystem. We can imagine that an individual tree in a ecosystem is an object or agent, has a set of behaviors related to establishment, growth, and death and response to its environment. Each individual tree has its own copy of behavioral code "genomes" that let it individually perceive the local environment, evaluate the input, and choose how to act. System-level constraints (e.g. spatial patterning in the distribution of primary environmental resources) can be applied, but these do not have to fully contain individual behavior, and individuals are 'allowed' to influence their local environment, with potential effects integrating up to larger scales. Furthermore, the environment and agent rules can be based on available studies and data. Dealing with mutli-scaled rules is also feasible, as exemplified by the our model's use of both meso- and topo-scaled environmental variables,

1.4 SWARM as a modelling environment to support agent-based simulation and object-oriented programming.

As noted above, implementation of this model was done within the Swarm package(see Nelso Minor et al). This is a multi-agent based simulation environment developed by a group of people engaged in complex system studies at The Santa Fe Institute. It aims to provide a framework for researchers in various disciplines to build agent-based simulation models to explore the emergent phenomena and dynamic properties of complex systems. The basic architecture of Swarm is a combination of collections of concurrently interacting agents or objects and a schedule of activity over those objects. It takes full advantage of object-oriented modelling and programming approaches, and is implemented using the dynamic object-oriented language Objective-C.

Swarm therefore is a collection of agents executing on a schedule of actions. Agents have the basic properties of information transfer, storage and processing. A typical agent is modelled as a set of functions or rules, responding to the message it receives. Also agents are able to adapt to their environment by changing their internal information processing functions through feedback loops of interactions just as individual organism do in the real world.

Swarm also supports hierarchical modelling approaches and accommodates multi-level models whereby agents can be composed of swarms of other agents in nested structures. Hierarchical models can be built by nesting multiple swarms at various levels.

We have found Swarm a powerful tool for modelling dynamic landscape ecosystems. A landscape can be organized into hierarchical integration levels with "is a" or "part of" relationships among different components at each level. For example, a tree is a species; a species is part of community; a community is a part of a patch; a patch is part of a landscape matrix etc. The landscape ecosystem can be defined in terms of the connections, interactions, and feedback loops among its components or agents.

The spatially explicit, dynamic simulation we have produced using Swarm is proving useful in observing how the local, non-linear interactions of many components or agents can develop into spatially and temporally complex landscape patterns.

1.5 Preliminary simulation results

The model is currently in its final stage of development, hence formal analytical experiments have yet to be conducted. But a trial simulation using sample data from a 1 by 1 km test area in the southern forest of Tasmania has shown that the basic features of spatial and temporal patterning in age classes and species diversity do emerged (see Figure 1, Figure 2 and the descriptions). More definitive analytical experiments are planned over the next 12 months.

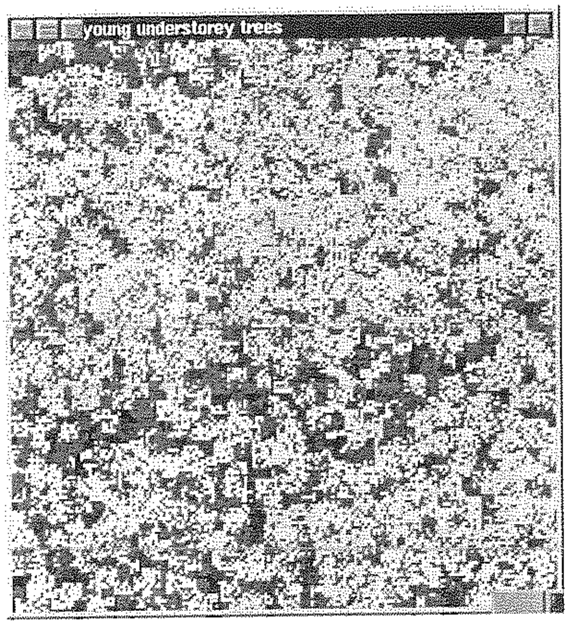

Figure 1. Screen shot from sample data simulation. It shows the spatial distribution of young forest understorey (age less than 20 years old) in the 1 by 1 kilometer area of Warra in Southern Tasmania. Different gray scale represents the distribution of different species (*Eucalyptus obliqua*, *E. Delegatensis*, *Acacia melanoxylon*, *A. dealbata*, *Atherosperma moschatum*, *Eucryphia lucida*, *Gahnia grandis*

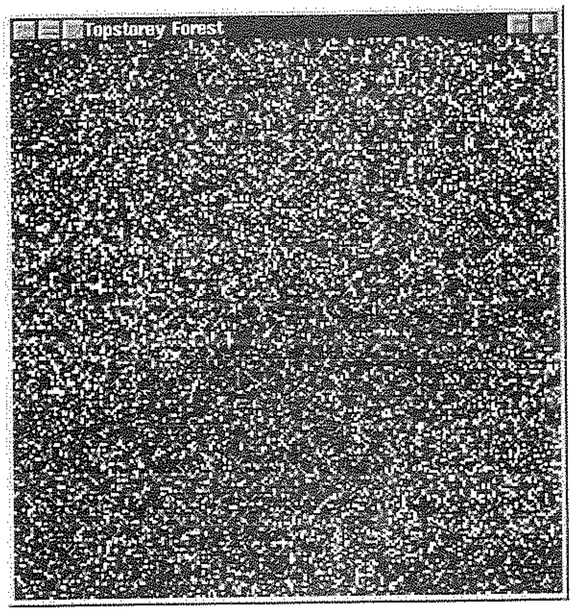

Figure2. The screen shot of the top forest(age great then 20 years old) from the same simulation. Species are the same. It clearly show that the spatial pattern in terms of species diversity emerged from the simulation.

1.6 Conclusion

Individual based object-oriented modelling is an efficient and appropriate approach to formulating simulation models of landscape ecosystem pattern and process, where location and individuals play an important role in the overall behavior of the ecosystem. Simulation modelling based on this methodology can help to further explore ecosystem dynamics and better describe and account for the interactions between spatial patterns and ecological process.

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