

Comparing methods for identifying optimal forest management

Mario Cammarano

*Institute of Agro-Environmental and Forest Biology,
Rome, Italy*

Goal

To compare the performances of a spatially explicit individual-based model and a model based on the perfect-plasticity approximation in predicting forest dynamics under different harvesting regimes.

Background and motivation

The past few decades have seen a considerable increase in the number and level of detail of individual-based models (IBMs) of forest dynamics. These models forecast dynamics by predicting each individual's birth, dispersal, growth, and death and how these events are affected by spatial competition for resources with neighbors. Individual-based forest simulators have also been used for forest management (Busing and Maily 2004).

Despite their usefulness, IBMs have one important disadvantage: they require too much computational resources to be used at a large scale. For this reason, a number of approaches have been recently developed based on differential equations, rather than on algorithms (Adams et al. 2007; Strigul et al. 2008; Purves and Pacala 2008). A notable advance in this area has been the development of the perfect-plasticity approximation (PPA; Strigul et al. 2008), which builds on the assumption that trees experience full light above the canopy height, defined as the maximum height at which the canopy can be closed, and a constant level of reduced light below the canopy height. In turn, the canopy height is a dynamic variable, and thus depends on demographic parameters.

Strigul et al. (2008) showed that a spatially explicit IBM that implements the perfect-plasticity approximation (PPA) gives results similar to those of a spatially implicit PPA model. The latter describes forest dynamics by the von-Foerster equation for the density of a size-structured population, together with an integral condition for the canopy height. They also compared predictions based on the PPA with results from the IBM SORTIE (Pacala et al. 1993). The SORTIE model describes trees as having a rigid cylindrical crown located directly above the stems. Quite unrealistically, full crown interpenetration is allowed, i.e., availability of space in the overstory is not a limiting factor. Pacala and Deutschman (1995) derived a mean-field approximation of the SORTIE model, but the comparison between the two approaches failed, suggesting that spatial effects cannot be described simply through averaged quantities. Interestingly, Strigul et al. (2008) compared the mean-field approximation based on the PPA with an extended version of the SORTIE model, which also accounted for crown plasticity and phototropism, and found the two to be in good agreement.

As the aforementioned findings indicate, the PPA is a promising tool for understanding forest dynamics. However, until now it has been developed and studied only for natural forest systems. In this project, we will explore its validity for describing managed forest under different types of harvesting. This will be done in three steps. First, we will develop a spatially-explicit IBM of forest dynamics that accounts for crown plasticity and management. Second,

we will derive a PPA approximation corresponding to this IBM. Finally, we will compare and critically evaluate the results of the two approaches.

Research questions

The two foci of this research project are comparison of different harvesting regimes and of methods for describing forest dynamics under management. The main research questions are summarized below:

- How do different harvesting regimes affect yield and harvesting costs, in particular as summarized by the resultant economic revenue?
- Given the high spatial symmetry underlying the PPA, can we expect that it gives a good description of forest dynamics under spatially symmetric cutting (e.g., clear-cutting)? Is the PPA also applicable under more complex, spatially heterogeneous harvesting regimes?
- Time permitting, we will also attempt to determine optimal management regimes that balance economic revenue with impacts on ecological and cultural ecosystem services.

Methods and work plan

Model structure

The spatially explicit individual-based model we will examine describes the dynamics of each tree in continuous time by considering birth, dispersal, growth, and death. Growth rates and mortality rates are affected by neighborhood competition, either through explicit light limitation as determined by the Beer-Lambert law, or through a proxy in the form of a competition index based only on mutual distances among trees (e.g., Pretzsch 2009). As we focus on a managed forest, birth and dispersal are determined entirely by the applied management regime.

The baseline submodels for tree growth, mortality, and mutual shading (i.e., light competition) will be defined according to two possible choices. The first option is to follow the physiological model developed by Falster et al. (2011), which has already been implemented as an IBM in a previous YSSP project. The second option is to develop the physiological submodels based on the SORTIE model. Crown plasticity will be added following Strigul et al. (2008).

Model implementation

Each tree has a horizontal position within the given plot. To avoid boundary effects, we consider periodic boundary conditions. The total time of a model run is divided into a discrete number of time steps, and the status of each tree is updated after each time step. As a large amount of computing time is required to identify each tree's neighbors, we will superimpose a discrete spatial grid on the plot such that the search for the neighbors of a focal tree can be limited to the neighboring cells of the focal tree (Pacala and Silander 1985; Bercé 2002).

Harvesting regimes

We will analyze the effects of different harvesting regimes on yield and harvesting costs, as summarized by economic revenue. The price of a harvested tree will be assumed to increase with stem diameter (and thus also with height). The harvesting cost will, at least initially, be assumed to be proportional to the number of harvested trees. Later, we may consider includ-

ing fixed expenses associated with harvesting operations, increased expenses associated with selective harvesting, and possibly also costs representing losses in cultural and ecological services.

The harvest regimes and control parameters to be analyzed are:

- A simple clear-cutting cycle, described by its frequency.
- Managed harvesting described by the frequency of harvesting and the fraction of trees removed at uniform spatial density.
- Selective harvesting based on size, described by a size-selectivity curve.
- Spatially non-uniform harvesting, described by a probabilistic model for the frequency of harvesting, as well as for the location, size, and shape of the harvested area.

Model visualization

Individual-based models can produce a large amount of data. Often, the most effective way to describe, explore, and summarize a large set of numbers is to visualize the information (Tufte 1983). Therefore, an important part of this project is devoted to the visualization of results. We plan to use OpenGL, a 3D graphics library in the C programming language, to provide a visualization of the modeled forest dynamics.

Work plan

The work plan is as follows:

- Definition of the basic physiological submodels that will be implemented in the IBM, following either the SORTIE model or Falster et al. (2011).
- Implementation of the OpenGL functions for visualization.
- Inclusion of crown plasticity in the IBM.
- Alternative description of shading and crown plasticity through the use of neighborhood competition indices.
- Inclusion of harvesting.
- Comparison with the PPA approach.

Relevance and link to EEP's research plan

Human-induced changes have the potential to profoundly alter the ecological environment of a species and thus also play a major role in shaping observed ecosystem patterns. Predicting the effects of such impacts may allow for better and more sustainable management of natural resources. This work thus aims to link ecological research with policy-relevant questions.

Expected output and publications

The results of this research project are intended for publication as a coauthored article in an international scientific journal. In addition, the developed visualization tool will be made available for future studies of spatially explicit vegetation dynamics.

References

Adams TP, Purves DW & Pacala SW (2007). Understanding height-structured competition in forests: Is there an R^* for light? *Proceedings of the Royal Society of London Series B* 274: 3039–3047

- Berec L (2002). Techniques of spatially explicit individual-based models: Construction, simulation and mean-field analysis. *Ecological Modelling* 150: 55–81
- Busing RT & Maily D (2004). Advances in spatial, individual-based modeling of forest dynamics. *Journal of Vegetation Science* 15: 831–842
- Falster DS, Brännström Å, Dieckmann U & Westoby M (2011). The influence of four major plant traits on average height, leaf-area cover, net primary productivity and biomass density in single-species forest: A theoretical investigation. *Journal of Ecology* 99: 148–164
- Pacala SW, Canham CD & Silander JA (1993). Forest models defined by field measurements: I. The design of a northeastern forest simulator. *Canadian Journal of Forest Research* 23: 1980–1988
- Pacala SW & Deutschman H (1995). Details that matter: The spatial distribution of individual trees maintains forest ecosystem function. *Oikos* 74: 357–365
- Pacala SW & Silander JA (1985). Neighborhood models of plant population dynamics. I. Single-species models of annuals. *American Naturalist* 125: 358–411
- Pretzsch H (2009). *Forest Dynamics, Growth and Yield*. Springer-Verlag, Berlin, Germany
- Purves DW & Pacala SW (2008). Predictive models of forest dynamics. *Science* 320: 1452–1453
- Strigul N, Pristinski D, Purves D, Dushoff J & Pacala S (2008). Scaling from trees to forests: Tractable macroscopic equations for forest dynamics. *Ecological Monographs* 78: 523–545
- Tufte ER (1983). *The Visual Display of Quantitative Information*. Graphics Press, Cheshire, USA