Balancing Ecology and Economy in Forestry:
A Theoretical Investigation

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Findings

- The size-structure and productivity of uneven-aged forests are strongly controlled by asymmetric competition for light between large and small trees.
- Ignoring the asymmetric competition effect leads to large overestimations of the potential to increase ecological value by increasing the diameter at which trees are harvested.
- Both for ecological and economic values it is optimal to harvest all trees at a certain diameter rather than harvesting many size-classes simultaneously.
- The Pareto-optimal harvesting strategies are confined to harvesting diameters above 50 cm corresponding to relatively low ecological impacts.
- The model provides a transparent and computationally efficient tool for evaluating the trade-off between ecological and economic values in uneven-aged forest management.

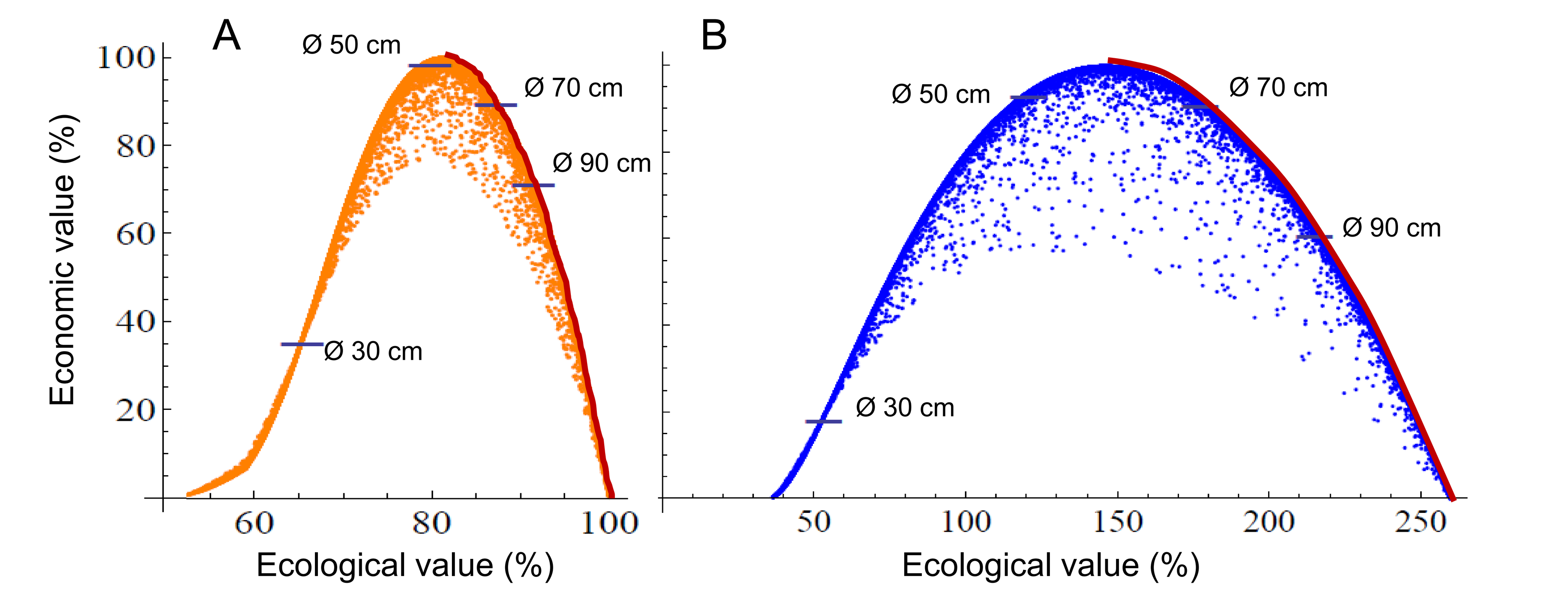

Figure 1. Economic and ecological values of a forest (red maple) subject to different harvesting strategies. Each dot represents a randomly selected strategy, defined by a minimum cutting diameter (Ø) and the fraction of trees cut per year. The Pareto-optimal strategies (red lines) are to cut all trees when they reach a certain diameter, Ø > 50 cm, where increasing Ø trades off economic benefit for ecological value. The PPA model (A) is compared to a similar model without light-competition (B), which overestimates the minimum Pareto-optimal Ø and the ecological benefit of increasing Ø. Economic value = timber value – harvesting costs, scaled with its maximum value. Ecological value = population tree-size variance relative to an undisturbed forest in the PPA model.

Background

While forests have traditionally been managed for wood production, there are good reasons to account also for other objectives, such as biodiversity conservation and other ecological values. In contrast to clear-cut based "normal" forestry, uneven-aged forest management can preserve a more natural structure and associated ecological values. However, due to the complex interactions among trees in such forests, optimal management modeling quickly becomes analytically intractable, and numerical investigations can prove an insuperable obstacle. A promising recent development to overcome this impasse is the perfect plasticity approximation (PPA, see below), which has opened a new avenue of ecologically realistic and analytically tractable forest models. Here we use a PPA based model to investigate the potential for combining economic and ecological values under uneven-aged forest management.

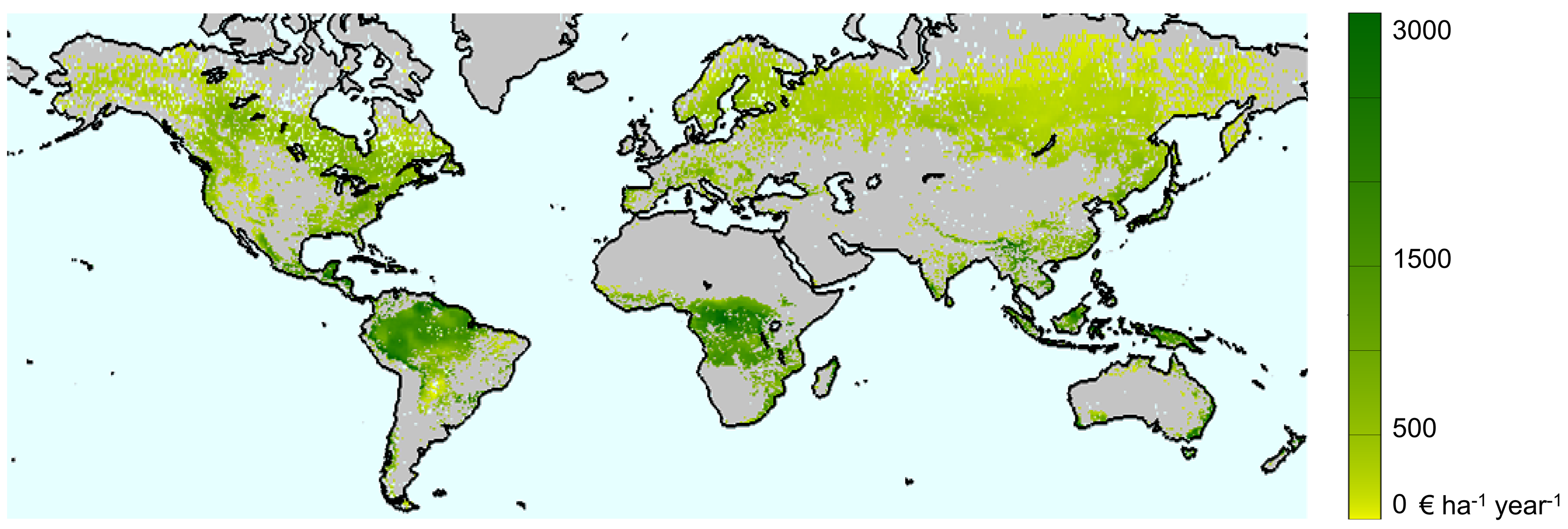

Figure 2. Potential net profits from timber harvesting under uneven-aged forest management modeled for all forested areas. The results are for economically optimal harvesting (see Fig. 1), which still only reduces the ecological value by approx. 10% in low productivity areas and up to 50% in high productivity areas. Tree growth is a function of net primary productivity (NPP; measured by MODIS 2006, processed by Ian McCallum at IIASA).

Model

The model is based on a standard representation of the dynamics of a size-structured population. To add the effect of size-asymmetric competition for light (that strongly controls the dynamics of most forests) in a tractable way, we used the perfect plasticity approximation (PPA, see below). To represent uneven-aged forest management the forest was assumed to be in steady state, i.e. approximating continuous harvesting causing no drastic fluctuations in forest structure.

General model equations

$N(D, t)$ is the density (number per m^2) of trees of diameter D at time t. The dynamics of the forest is defined by:

$$\frac{\partial N(D,t)}{\partial t} = -G_u \frac{\partial N(D,t)}{\partial D} - (\mu_u + c(D))N(D,t) \text{ if } D < D^* \quad (1a)$$

$$\frac{\partial N(D,t)}{\partial t} = -G_c \frac{\partial N(D,t)}{\partial D} - (\mu_c + c(D))N(D,t) \text{ if } D \geq D^* \quad (1b)$$

In eq. 1, G and μ are growth and mortality rates, respectively, where the indices u and c denotes below and above the critical height (h^*, fig. 3). $c(D)$ is the cutting rate. D^* is the critical diameter, i.e. D for trees with $h = h^*$, defined by:

$$\int_{D^*}^{\infty} A(D)N(D,t)dD = 1 \quad (2)$$

Equation 2 reflects the size-structured competition for light which occurs implicitly in the model: once the tallest individuals have filled the canopy, the remaining individuals are assumed to be in the understory where light availability is reduced. Recruitment of new trees (reproduction) is:

$$N(D_0, t) = \frac{1}{G_u}\int_{D_0}^{\infty} N(D,t)A(D)F(D)dD \quad (3)$$

In eq. 3, $F(D)$ is fecundity per crown area and $A(D)$ is the crown area.

Equation 4 conserves mass across the growth-rate discontinuity at D^*:

$$\lim_{D\to D^*_-} G_u N(D,t) = \lim_{D\to D^*_+} G_c N(D,t) \quad (4)$$

The perfect plasticity approximation (PPA)

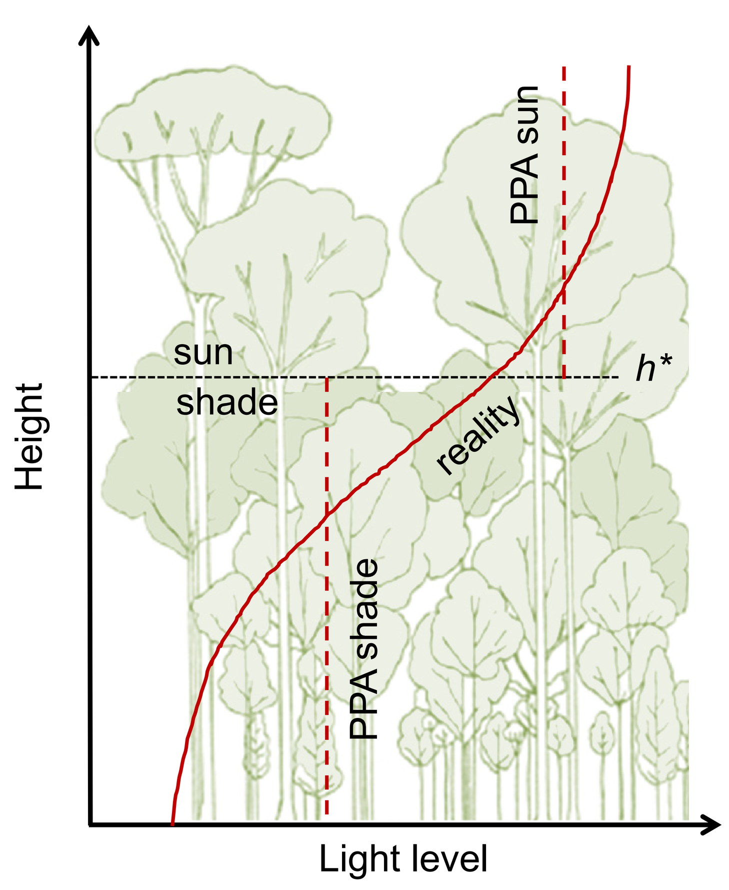

Figure 3. The perfect plasticity approximation (PPA) of light competition. In a forest stand available light declines exponentially down through the canopy, which leads to a very strong difference in light absorption between tall and short trees. In the PPA this light gradient (solid red line) in the canopy is approximated by just two light levels (dashed red line), sun and shade, where the switching height (h^*) is defined as the height where the accumulated area of all leaves above h^* covers the ground area. This approximation simplifies the modeling of light competition among trees enormously while still retaining the essential feature that taller trees suppress shorter trees by shading them[1].

[1]Strigul, N., D. Pristinski, D. Purves, J. Dushoff and S. Pacala 2008. Scaling from trees to forests: Tractable macroscopic equations for forest dynamics. Ecological Monographs. 78:523-545.