Using an Individual-Based Model of Uneven-Aged Forests for Studying Trade-off Between Timber Production and Deadwood Preservation

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Abstract—**Integrating the multi-functional role of forests in forestry practices constitutes a challenging example of complex system management. Usually, win-win situations between functions are seldom and trade-offs have to be considered. This paper proposes a framework to study dynamical relationships between two important functions in forests: timber production and biodiversity conservation. We built an individual-based model of uneven-aged forests that explicitly takes into account timber harvesting options and dead wood dynamics. Dead wood compartment was selected because it represents a relevant surrogate for biodiversity in forests. We used dynamics metrics based on viability theory framework to evaluate simulations that contrasted different thinning intensities and thinning frequencies. Thanks to this model and the metrics used, we are able to discuss optimal strategies for preserving biodiversity while guaranteeing timber production.**

Keywords-Individual-based model; complexity; forest management; multi-functional performance.

I. INTRODUCTION

Multi-functional management is a challenging issue, which can be generalized for most social-ecological systems. The multi-functional paradigm of forest management is nowadays very common. Forests have multiple roles and provide multiple services for society, including not only timber production but also species conservation. Proposing tools that allow forest managers to fulfill different functions in a given place is therefore of growing concern [1][2]. However, models cannot represent all functions and thus, simulation studies can hardly determine the best choice to make [1]. Nevertheless, models can be used to better understand or evaluate different situations regarding to a specific point of view.

In this paper, we try to provide a common framework to researchers and decision makers, who want to evaluate forest management units regarding to two functions: timber production and biodiversity preservation. Our aim is to Specify entirely the model and the indicators used, in order to enables researchers to modify both, silvicultural scenarios, and forest dynamics model parameters. Hence, it will be possible to evaluate and compare different contexts, based on the common rigorous and explicit theoretical framework provided by the model specification.

Consequently, the objective of this paper is: i) to propose an individual-based model that enables the evaluation of forest management within the framework of multi-functionality; ii) to discuss the trade-off between timber production and biodiversity preservation using a risk-based performance criteria to evaluate forestry practices. From the point of view of renewable resource management, we use the viability theory framework of resilience [3] to establish system performance criteria representing ecological biodiversity resilience [4]. This kind of approach is also related to the concept of permanence already used to evaluate forest capacity to ensure several functions [5].

The paper is split in four parts. In Section II, we present the general method adopted. In Section III, we present and specify the model used to simulate forest dynamics. In Section IV, we present and specify the forest management algorithm. Finally, in Section V, we present simulations results.

II. MATERIAL AND METHOD

Forest dynamics modelling and simulation have been widely studied during these past years, providing spatial models of forests, validated for several tree species and forest management types. Those models can be used to test and understand trade-offs offered by some given forestry practices, regarding to some given functionalities [6].

However, these models cannot take into account all the functions of the forest, which can be defined at different spatial scales. For this reason, instead of trying to find the best trade-off between ecosystem services [1][6], we rather try to identify the solutions that better provide all services considered, i.e., solutions that are not pareto-dominated. The set of solutions found can then be used as a reference to make decision. Following this approach, we do not need to use commensurable criteria to evaluate the different services provided by the forest. Particularly, it enables us to use dynamics metrics adapted to each service considered. We can thus represent the fact that, for instance, the timber production function can be averaged over time, whereas the

insect habitat providing function must be permanently supplied.

Consequently, our methodological proposal is to design a simple individual-based model to simulate trajectories of these indicators for forest stands managed under different silvicultural scenarios. Applying dynamics metrics to these trajectories, we are able to compare the criteria values for the different scenarios.

We first identify the indicators to be monitored, in relation to the timber production and biodiversity preservation functions. The indicator chosen to monitor timber production is the harvested timber volume (V_r) at each time t. Only the mean value of this indicator is important here: the dynamics of stand timber production is not important because wood supply permanency should be evaluated at a wider spatial scale than the one considered in silvicultural management. Consequently, the performance criteria considered for timber production is the mean harvested timber volume over a given period ($\bar{V}_r$). We chose two indicators related to the biodiversity preservation function. In a review dedicated to indicators of biodiversity for ecologically sustainable management, Lindenmayer et al. [7] suggests two categories of indicators: taxon-based indicators based on the presence/absence of some species, and structure-based indicators based on the structure of habitats at the stand or landscape scale. Here, we decided to focus our work on structure-based indicators. We focus on two habitats known to be linked to the biodiversity of saproxylic beetles (beetles that depend on dead wood) [8][9][10]: the average dead wood volume in the stand, denoted I_1, and the volume of adult dead trees in the stand (i.e., number of dead trees with diameter greater than 17.5cm), denoted I_2.

Both indicators (I_1 and I_2) can be monitored over time. We use resilience criteria for providing a way to compare dynamic trajectories of the indicators. For each structural indicator I_1 and I_2, we consider a minimum value I_1^{min} and I_2^{min} and we compute a resilience criteria $\gamma(I_k)_{k=\{1,2\}}$, as the percentage of time, during which the minimum acceptable value is not reached, over a given time period T (1).

$$\gamma(I_k) = \frac{E\left[\!\left[\int_0^T \mu(I_k(t))\,dt\right]\!\right]}{T} \qquad (1)$$

where,

$$\mu(I_k(t)) = 1 \text{ if } I_k(t) > I_k^{min}$$
$$= 0 \text{ otherwise}$$

Mathematical expected value $E\left[\!\left[\int_0^T \mu(I_k(t))\,dt\right]\!\right]$ is computed as an average over several replications of the model, which involves stochastic processes. This resilience criterion highlights the ability of the system to continuously provide saproxylic habitats despite of cyclic timber removals.

III. MODELLING FOREST DYNAMICS

We consider a mono-specific uneven-aged forest. We use a spatial individual-based model, which takes into account interactions between trees. It is a demographic model, which simulates the processes of growth, mortality and recruitment. We choose a diameter-based dendrometric model because it has a low computational cost, compared to more compex individual-based models. The growth sub-model is based on the simplification of the *Samsara2* model developed for Norway spruce and Silver fir in French mountain forest [11]. Other processes are calibrated to obtain qualitative results similar to the *Samsara2* model.

A tree k (adult or juvenile) is characterised by its position in the 2D space (we write $x_k \in R^2$) and its diameter at breast height: $d_k \in R$. We also consider coarse woody debris characterised by a volume $v_{w,k}$, a diameter $d_{w,k}$ and an age $a_{w,k}$. Coarse woody debris can be either a dead tree (wind-throw, other natural death, ..) or parts of a tree that have been removed. We do not consider this distinction in this study. System state at time t is then characterised by the tree population of N_t trees $(x_k, d_k)_{1<k<N_t}$ and the coarse woody debris population of N_w coarse woody debris $(v_{w,k}, a_{w,k}, d_{w,k})_{1<k<N_w}$.

Thereafter, we use basal area instead of diameter without any loss of information. The basal area is a value commonly used in forest management and measures the cross-section of tree trunks and stems at 1.30m hight. Basal area of tree k is noted g_k and computed as specified in (2).

$$g_k = \frac{\pi d_k^2}{4} \qquad (2)$$

A diameter-volume function noted $V(d)$ enables us to convert diameter values to volume values. We used a simple classical volume tariff called Algan n°9 for diameters greater than 15cm and linearised this tariff for diameters smaller than 15cm. This function is parametrised with a circumference metric decrease of 6 cm per meter.

A. Competition

For all processes, a perfect one-sided competition $C(x_k, d_k)$ expressed in (m^2/ha) was considered, as specified in (3).

$$C(x_k, d_k) = \sum_{i|d_i \geq d_k} g_i \omega(x_i - x_k) \qquad (3)$$

where ω is a light interception kernel designed as a spatial kernel of parameter σ:

$$\begin{cases} \omega(x'-x) = \dfrac{1}{\pi\sigma^2}, & if \ \|x'-x\| \leq \sigma \\ \quad \omega(x'-x) = 0, & otherwise \end{cases} \qquad (4)$$

B. Growth process

The growth process equation used for all trees (diameter greater than 7.5cm) is given by the basal area growth, computed as a potential growth *Pot*, multiplied by a reduction function *Red* (5 to 7). The potential function used is the potential growth used in the *Samsara2* model [11]. The reduction function *Red* has been chosen for its simplicity and calibrated to obtain similar simulation results as the *Samsara2* model using perfect one-sided competition.

$$\frac{dg_k}{dt}(x_k, d_k) = Pot(x_k, d_k) * Red(x_k, d_k) \tag{5}$$

with

$$Pot(x_k, d_k) = r_0 \frac{d_k^{r_1}}{1 + r_2 e^{r_3 d_k}} \tag{6}$$

and,

$$Red(x_k, d_k) = u_0 e^{-u_1 C(x_k, d_k)} \tag{7}$$

where, $(r_i)_{(0 \leq i \leq 3)}$, and $(u_i)_{(0 \leq i \leq 1)}$ are species specific parameters related respectively to potential growth and competition.

C. Mortality process

A logistic model is used for mortality. Probability of mortality per year *P* is given in (8).

$$P(x_k, d_k) = \max\left(P_1(x_k, d_k), P_2(x_k, d_k)\right) \tag{8}$$

This mortality function is composed of two functions *P₁* and *P₂* designed respectively for young trees and old trees. *P₁* is based on the French forestry inventory data from IFN (the regression method is not detailed here). Forestry inventories mostly contain small and medium diameter trees. According to literature, large tree mortality is higher than the mortality of small trees. Thus function *P₂*, is used to correct mortality rate for large diameter trees. $P_1(x_k, d_k)$ and $P_2(x_k, d_k)$ are given in (9) and (10).

$$P_1(x_k, d_k) = \frac{1}{1 + e^{p_0 + p_1 . d_k - p_2 . d_k^2 - z . C(x_k, d_k)}} \tag{9}$$

$$P_2(x_k, d_k) = \frac{1}{1 + e^{-p_3 - p_4 d_k^2}} \tag{10}$$

where $(p_i)_{(0 \leq i \leq 4)}$ and z are species specific parameters related respectively to potential death and death linked to competition.

D. Recruitment process

Trees are recruited with a diameter of 7.5 cm. The probability that a tree is recruited in a position *x'* depends on the past environmental conditions at this position. We consider the number of seeds that have been spread at this position and the competition that this position has been subjected to over the past twenty-five years. At time t_0 each tree *k* can recruit a young tree situated in a free position x' with the probability $R(x', x_k, d_k, t_0)$ computed as in (11).

$$R(x', x_k, d_k, t_0) = \frac{b . g_k \sum_{t=t_0-24}^{t_0} \omega_D(x' - x_k) e^{-sC(x',7.5)}}{25} \tag{11}$$

where b is the potential recruitment rate; s is the sensitivity to light; C(x',7.5) is the local competition for light on the position *x'* for a tree of diameter inferior than 7.5 cm as presented in (3); ω_D -function is a dispersal function computed as a spatial kernel of parameter σ_D as the ω function presented in (4).

E. Coarse woody debris generation and decomposition

Each time a tree (x_k, d_k) dies, a new coarse woody debris *i* is generated with: $v_{w,i} = V(d_k)$, $d_{w,i} = d_k$ and $a_i = 0$.

Once a coarse woody debris has been generated, it is subjected to natural decomposition and its volume decreases according to (12).

$$\frac{dv_{w,k}}{dt} = -\alpha . v_{w,k} \tag{12}$$

where α is the decomposition rate. Furthermore, any coarse woody debris with $v_{w,k} < 0.0001$ m³ is removed from the system. Age of the dead wood piece increases with time as described in (13).

$$\frac{da_{w,k}}{dt} = dt \tag{13}$$

IV. MODELLING FOREST MANAGEMENT

In this part, we model management actions on the forest stand. The minimum diameter for removal is noted D_{min}. In the following, we note V_r the total volume removed. We consider a simplified view of forestry practices performed in the case of uneven-aged forest management (see [11] for a more complete simulation of uneven-aged management). A silvicultural scenario is defined by a removal intensity (removal stops when a total of Δba per year has been removed) and the minimum interval during two removals (Δ_t). To these forest management factors, we add 2 factors for dead wood management:

- p_a is the proportion of the dead wood basal area removed at each removal. This is related to the possibility of removing some recently dead trees. This parameter is interesting regarding conservation strategy (i.e., dead tree retention or not);

- p_e is the proportion of wood volume exported when a tree is removed. Meaning that ($1-p_e$) stays on the stand. This parameter can be related to biomass energy practices (i.e., whole tree extraction or not).

A. Removal decision

At time t, we note V_{cwd} the set of deadwood removable during the previous Δ_t time period:

$$V_{cwd} = \{(v_{w,k}, a_{w,k}, d_{w,k}) \mid d_{w,k} > D_{min} \text{ and } a_{w,k} < \Delta_t\} \quad (14)$$

Then the basal area available for removing can be approximated by the value BA_a:

$$BA_a = \sum_{i|d_i > D_{min}} g_i + p_a \sum_{j|(v_{w,j}, a_{w,j}, d_{w,j}) \in V_{cwd}} \pi \frac{d_{w,j}^2}{4} \quad (15)$$

The removal decision is the following:

"A removal is performed at time t if and only if at this time $BA_a \geq \Delta ba$ AND the time spent since the previous removal is greater than Δ_t."

If $BA_a < \Delta ba$ when the time step since the previous removal is Δ_t, the removal period is increased continuously until the date t_0, for which $BA_a \geq \Delta ba$. Then, the same procedure occurs at time $t_0 + \Delta_t$.

B. Removal process

First, dead trees to remove are successively withdrawn from the set V_{cwd} by decreasing order of diameter, until the proportion p_a of the total basal area of V_{cwd} is reached. Whenever a dead tree k is removed at time t, we observe the updates described by (16) to (18).

$$v_{w,k}(t+dt) = (1-p_e)v_{w,k}(t) \quad (16)$$

$$d_{w,k}(t+dt) = D_{min} \quad (17)$$

and

$$V_r(t+dt) = V_r + p_e v_{w,k}(t) \quad (18)$$

Then, Δba living trees with diameter greater than D_{min} are randomly selected and harvested until Δba is reached, unless Δba has already been reached with dead trees. The probability P_k that an individual k is

removed at each successive step is given in (19) (see [11] for a justificaiton):

$$P_k = \left(\frac{d_k}{max_{i \in S} d_i}\right)^2 \quad (19)$$

where $S \subset \{(x_i, d_i) \mid d_i \geq D_{min}\}$ is the set of trees that have not been removed. When a tree k is removed, a new dead tree l is created. Its volume is $v_{w,l} = (1-p_e)V(d_k)$, and its diameter is D_{min}. Then, the removed volume is increased as follows:

$$V_r(t+dt) = V_r(t) + p_e V(d_k) \quad (20)$$

where $V(d_k)$ is given by the volume computation function.

V. RESULTS

A. Experimental design

We performed simulations with parameter values described in Table 1. Initial states are obtained by simulating 2000 years with no management, followed by 1750 years with the chosen management strategy. It enables us to reach pseudo-equilibriums of managed forests. With this experimental design, we tested three different values for harvested quantities, presented as a yearly basal area harvested (Δba), as well as for the minimum removal period (Δ_t). Tested values are presented in Table 2. Nine different strategies are defined from the combination of these factors. In addition, a scenario with no removal is presented. Twenty replications were performed for each removal strategy.

TABLE I. VALUES OF THE PARAMETERS

D_{min}	p_a	p_e	d_0	d_1	d_2	d_3	r_0	r_1	r_2
27.5	0.9	0.9	-4.37	-0.014	4.10^{-4}	-9	9.64	0.24	1.11

r_3	u_0	u_1	b	s	σ	σ_D	α
-0.10	0.85	0.035	11	0.05	10	15	0.07

TABLE II. VALUES TESTED FOR THE TWO SIVICULTURAL FACTORS

Δba^{min} (m².ha⁻¹.year⁻¹)	0.2	0.4	0.6
Δ_t (year)	5	10	15

For each combination of factors values, we computed the timber production criterion $\bar{V}_r$ and the two biodiversity preservation criteria $\gamma(I_1)$ and $\gamma(I_2)$. As said previously, the first indicator (I_1) is the total volume of deadwood on the stand. It can be computed at any time step as presented in (21).

$$I_1 = \sum_{0 \leq k \leq N_w} v_{w,k} \quad (21)$$

A minimum value of 15 m³/ha of dead wood in European forest stands seems to be reasonable regarding to actual knowledge [12]. Consequently, I_1^{min} is equal to 15m³.

The second indicator (I_2) does not correspond to a specific recommendation, but enables us to discuss about a qualitative aspect of the dead wood stock. As dead wood diversity plays an important role in saproxylic beetles diversity [10], we monitor the volume of adult dead trees on the stand:

$$I_2 = \sum_{[k|d_{w,k}>17.5]} v_{w,k} \qquad (22)$$

We chose a limit of 4 m^3 corresponding to the mean volume of two adult dead trees. Consequently, I_2^{min} is equal to 4m^3.

B. Simulation results

The mean timber production and the resilience of the dead wood stock $\gamma(I_1)$ (% of time in which dead wood volume is greater than 15 m^3) for each removal strategy are presented in Figure 1. The scenario without any removal is represented in this Figure as a green diamond. We can see that in this case the production is null and the dead wood stock resilience is 100%, meaning that the volume of the dead wood stock (I_1) is always greater than 15 m^3 (I_1^{min}) for this scenario.
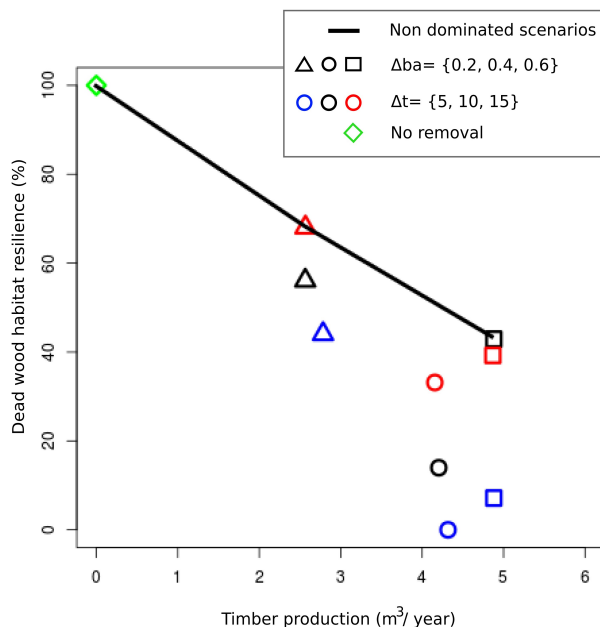

Figure 1. Timber mean production and dead wood habitat resilience for different removal strategies.

We first notice that increasing the time lap between removals has a low impact on production (less than 5%), but increases dead wood habitat resilience. It is mainly due to the fact, that increasing time lap between removals enables the system to regenerate deadwood, despite of the regular timber removals. However, for Δba =0.6, high time laps (Δ_t =10 and Δ_t =15) between timber removals, lead to equivalent value of the resilience criteria.

Then, increasing the harvest basal area leads to a non-linear increase of the timber production, whereas it decreases

the dead wood stock resilience indicator $\gamma(I_1)$ in most cases. However, increasing the harvest basal area from 0.4 m^2.ha^{-1}.y^{-1} to 0.6 m^2.ha^{-1}.y^{-1} does not increase the production criteria, as much as increasing it from 0.2 m^2.ha^{-1}.y^{-1} to 0.4 m^2.ha^{-1}.y^{-1}. The first reason is that the higher the removal intensity is, the younger (and thus the smaller) the trees are. Consequently, for the same harvest basal area, the timber volume removed is lower. The second reason is that the whole basal area of 0.6 m^2.ha^{-1}.y^{-1} cannot be harvested at every removal period. Consequently the removal period is increased, in respect to the removal algorithm, until the harvest basal area is available. This is the reason why, even if the mean timber production is higher, resilience indicator $\gamma(I_1)$ for Δba =0.6 is higher than that for Δba =0.4. Interval between removals is increased and thus resilience is higher.

Figure 2 shows the same results but considering the volume of adult dead trees, instead of the whole dead wood volume (% of time in which adult dead trees ($d_{w,k}>17.5$ cm) volume is greater than 4m^3). Once again, the resilience indicator is 100% in the scenario with no removal. Like $\gamma(I_1)$, $\gamma(I_2)$ increases when the time lap between removal increases. However, unlike $\gamma(I_1)$, excepted for the five year removal period where the same phenomenon occurs, adult dead trees resilience is higher for an average harvest basal area (circles), than for a high removal (squares). This is due to the fact that, when high values of basal area are removed at the same time, most of adult trees are removed, and thus the forest is mostly composed of young trees.
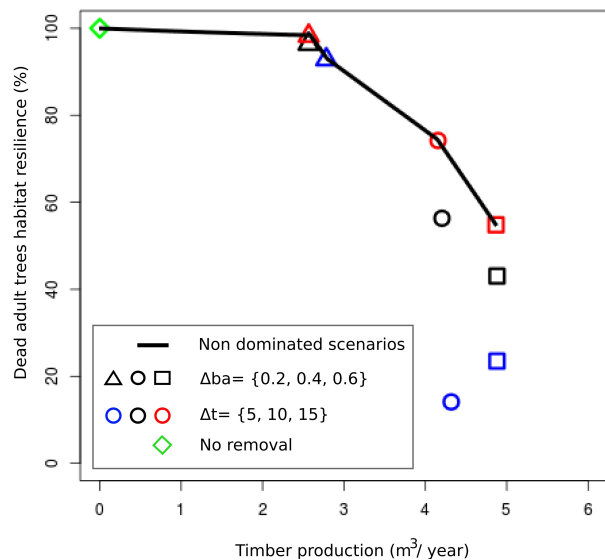

Figure 2. Timber mean production and adult dead trees habitat resilience for different removal strategies.

Finally, Figures 1 and 2 enable us to identify silvicultural scenarios that are non-dominated by neither a criterion nor the other. These scenarios are linked by black lines in both Figures. In regard to these two functions, preferred scenarios chosen should be on these lines. Furthermore, pareto-

dominated scenarios can be compared relatively to their distances to the non-dominated scenarios for each criteria.

VI. CONCLUSION

Multi-functional forest management raises several issues, at the political point of view, to design forest management policies at regional scales, as well as at the technical point of view, to design forestry practices at the management unit scale.

We developed a simple individual-based model, in order to test the impact of forestry practices on indicators linked to timber production and biodiversity resilience. We showed that this model enables decision makers, to discuss the trades-off offered by different forestry practices, concerning timber production and some indicators of biodiversity preservation.

Beyond forest management, the multi-functional management issue can be extended to most social-ecological systems [13]. Considering the more general problem of multi-functional socio-ecosystem management, we think that this work provides an interesting point of view, where a generic model is designed to evaluate multi-criteria decisions when criteria are not commensurable and similar situations are numerous.

One of the main advantages of this model lies in the spatialization of processes. It will enable us to consider more complex forestry practices. Besides, in future work, we plan to propose and test adaptive forest managements, relying on simple indicators that the forest manager can easily estimate, such as the potential biodiversity index developed for assessing potential biodiversity in forest stands [2].

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