BETA
Bureau
d'économie
théorique
et appliquée

Documents
de travail

« Forest harvest intensification and expansion: Modeling land-use change in heterogeneous regions»

Auteurs

Charis Anais Kanellos, Philippe Delacote,
Antonello Lobianco, David. W Shanafelt

Document de Travail n° 2026 – 13

Avril 2026

Bureau d'Économie
Théorique et Appliquée
BETA

https://www.beta-economics.fr/

Contact :
jaoulgrammare@beta-cnrs.unistra.fr

Forest harvest intensification and expansion : Modeling land-use change in heterogeneous regions

Charis Anais Kanellos[1*†], Philippe Delacote[1],
Antonello Lobianco[1], David. W Shanafelt[1†]

[1*]Université de Lorraine, Université de Strasbourg, AgroParisTech,
CNRS, INRAE, BETA, 54000, Nancy, France .

*Corresponding author(s). E-mail(s): charis.kanellos@inrae.fr;
Contributing authors: philippe.delacote@inrae.fr;
antonello@lobianco.org; david.shanafelt@inrae.fr;
†These authors contributed equally to this work.

Recent bioenergy policies have led to an increase in wood demand, the use of which is linked to sustainability and climate change objectives. However, balancing climate mitigation and wood harvest involves land use competition among sectors (e.g. agriculture vs forestry) and within sectors (e.g. resource exploitation and conservation). By developing a theoretical model of natural resources management and conducting numerical simulations, we show how initial land allocation impacts forest expansion and intensification choices in two regions. In particular, we analyze optimal land allocation (between primary, secondary forest and agriculture) and timber harvest intensity under scenarios of increased wood demand, harvest restriction in primary forest and tree mortality, including quantifying the marginal rates of substitution between harvest intensity and forest expansion and between primary and secondary forest. The initial land allocation does not significantly affects forest management decisions. As wood demand increases, the profitability of wood production rises, resulting in a combination of deforestation and higher harvested volumes. In our model, secondary and primary forests behave as substitutes: secondary forests can be harvested in lieu of primary forest to meet timber demand. These findings underscore the need for sustainable harvesting practices and policies, especially as forest resources face growing pressure from climate change, rising timber demand, and regulatory constraints.

Keywords: forestry, land allocation, agriculture, sustainable resource management
JEL codes: Q23 (Forestry); Q3 (Nonrenewable Resources and Conservation); Q5 (Environmental Economics)

1 Introduction

Recent bioenergy policies have led to an increase in wood demand, such as the European Renewable Energy Directives (RED), which proposed to double the share of renewable energy (including wood-based biofuels) in the energy mix by 2030, compared to 2020 levels[1]. Broadly speaking, the use of wood products is increasingly linked to sustainability and climate change objectives, as wood products are seen as substitutes to fossil fuels and non-wood materials [1–3]. In order to meet this new demand, policy makers and land managers must balance competing objectives within the constraints of limited land availability, such the demand for wood or climate mitigation goals (forest) and the need for agricultural products to feed a growing population (farmland). Tradeoffs between wood production and forest conservation leading to land use changes such as deforestation [4]. For instance, bioenergy policies can increase the demand for cropland, accelerating deforestation rates [5]. These trade-offs are often exacerbated by the effects of climate change, such as droughts, soil erosion, and hurricanes, which increase resource vulnerability and reduced soil productivity [6].

Additional wood demand can be met by either intensifying management practices or by extending productive forest area. The former involves increasing land productivity through the modification of forest management practices, such as reducing rotation periods, increasing harvest levels, or altering forest structure and species composition (e.g., planting faster growing species) [7]. The latter refers to the expansion of timber production to new areas, often involving the conversion of primary forest into timber plantations or logging areas, particularly in developing countries [8]. Indeed, the proportion of managed forest and management intensity are expected to rise with growing global demand for wood products [9]. For instance, harvest intensification is increasing despite afforestation policies in Europe [10], permitting forest conservation while sourcing increased timber demand. However, both harvest intensification and forest expansion involve tradeoffs. For instance, high harvest intensity may increase timber production but decrease biodiversity [11, 12] and carbon stocks [13]. While forest expansion can enhance carbon sequestration, it is constrained by the availability of suitable land [14].

In this paper, we adopt a simplified forest transition model with forest harvest intensity to study the tradeoffs associated between allocating land between primary and secondary forests and agriculture. Specifically, we seek to answer three research questions. First, how does the initial land use allocation and the structure of benefits and costs of each land use type drive forest management policy ? Second, how do timber production or forest conservation policies, alter our baseline land use allocation and harvest trajectories? Finally, what is the effect of tree mortality (such as that due to climate change) on timber production choices in secondary forests?

Our paper fits into three branches of the literature that deal with forest expansion and forest management, albeit from different perspectives (Supplemental Material A). First, the forest transition literature analyzes long-term land use changes and trade offs between forests and agriculture. [15] originally proposed the forest transition theory as a historical generalization to help explain recent changes in forest

---

[1] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32023L2413

cover [16]. This theory outlines a typical trajectory of forest stock over time. In the early stages of economic development, population growth and agricultural expansion lead to deforestation. However, as economies industrialize, rural populations migrate to urban areas, agriculture becomes more intensive, and previously cultivated land is often abandoned and gradually reforested. Numerous empirical studies have examined this theory [17, 18]. [19] identified two key drivers of forest transition: economic development and forest scarcity. Supporting the ideas of [20], they argue that economic development promotes urbanization and agricultural decline, which in turn enables forest regeneration. The theory has also been expanded from a theoretical perspective. Building on the foundational work of Mather and others, [21] proposed a broader framework in which forest transition is driven by shifts in relative land values, forest cover changes as the profitability of forested land compared to alternative uses fluctuates over time. More recently, [22] distinguished between primary and secondary forests to better understand the dynamics of forest transition. However, this literature studies changes in forest area but does not explicitly consider the intensity of timber harvesting.

The second is the optimal forest management literature. Forest management was first studied by Faustmann (1849), who defined the optimal rotation age of a parcel of forest by maximizing the present value of expected profits over an infinite time horizon [23]. The Faustmann rotation model has since been extended to consider non-timber benefits [24], carbon taxes and subsidies [25], intermediary forest treatment costs [26], and uncertainty in future states of nature [27, 28]. This literature analyzes the optimal rotation of a forest stand, but do not consider land-use change.

Finally, a set of more complex forest-sector models exist that consider more diverse markets and methods of forest management across spatial scales, such as the Forest French Sector Model (FFSM) [29–31], the Global Timber Market model [32], and integrated assessment models [33–36]. Models like GLOBIOM or the Global Change Assessment Model (GCAM) exist between forest expansion and forest management models, as they model land use change considering different types of forest management types (unmanaged, managed forest and plantations) and different sectors of the economy (e.g., agriculture, population growth etc). These models are frequently used in policy analysis because they can capture the complex interactions between human activities and environmental systems [37–39]. However, their closeness to real-world conditions can make it difficult to isolate specific trade-offs, as their outputs result from the interplay of many interacting variables.

Our contribution is to bridge the gap between forest transition and optimal forest management approaches. We integrate a variable of forest harvest intensity in a forest change model such that, the land planner chooses how to allocate land between forest types and agriculture, with the additional notion that s/he is able to decide how to manage secondary forests for timber. The resulting model is a dynamic, non-linear optimization problem that maximizes net social welfare, considering both non-renewable resources (primary forest) and renewable resources (secondary forest and agriculture. The land planner incurs management costs for each land use type but gains direct benefits from agricultural production and timber production in secondary forests, as well as indirect, non-consumptive benefits from forests (e.g., ecosystem services). Using a simple framework, we hope to illustrate the economic trade-offs involved in land use changes and forest management intensity.

The rest of the paper is organized as follows. Firstly, we present the theoretical modelling framework and describe the scenarios implemented (section 2). In section 3, we present our results, beginning with the effects increased timber demand (scenario 1), restrictions on primary forest harvest (scenario 2), and tree mortality in secondary forest (scenario 3). We discuss our results in section 4 and conclude the paper.

2 Methods

2.1 A forest transition model with harvest intensity

Consider a land planner who manages a large patch of land of a fixed area, the use of which is allocated between primary forest (i.e. natural and unharvested forest), secondary forest (i.e. even-aged plantations) and agriculture. The areas of each at time t are given by the variables F_t, S_t and A_t such that $F_t + S_t + A_t =$ total land. Furthermore, the volume of harvestable timber in secondary forest is given by the variable V_t, where we assume that the total standing volumes of each type of forest are harvestable. These are the state variables of our model.

At each moment in time, the planner chooses how much land to allocate to each land use type, as well as how much wood to extract from secondary forest to maximize net social welfare. To do so, the land planner chooses how much area of primary forest to clear cut (d_t) and convert to agriculture $(\alpha)^* d_t$ or secondary forest $(1-\alpha)^* d_t$, how much area of agriculture to convert to secondary forest (r_t), how much area of secondary forest to convert to agriculture (a_t), and the quantity of wood (in volume) to harvest from secondary forest (h_t). We provide a visual representation of the land use dynamics of the model in Figure 1.

Equations governing the change in area of primary forest, secondary forest, and agriculture are given by,

$$\dot{F}_t = -d_t \tag{1}$$

$$\dot{A}_t = \alpha * d_t - r_t + a_t \tag{2}$$

$$\dot{S}_t = (1-\alpha) * d_t + r_t - a_t \tag{3}$$

We treat primary forest as a non-renewable resource. Once it is lost, it can never be recovered. Furthermore, we assume that when primary forest is converted to other land uses, its area is reallocated at a constant proportion between agriculture α and secondary forest $(1-\alpha)$, where $0 \leq \alpha \leq 1$[2].

The volume of harvestable wood in secondary forest can be represented as an aggregation of individual forest stands of different ages and species, whose volumes

---

[2] To simplify the analytical analysis, we fix the value of α at a constant rather have it vary over time as a control.

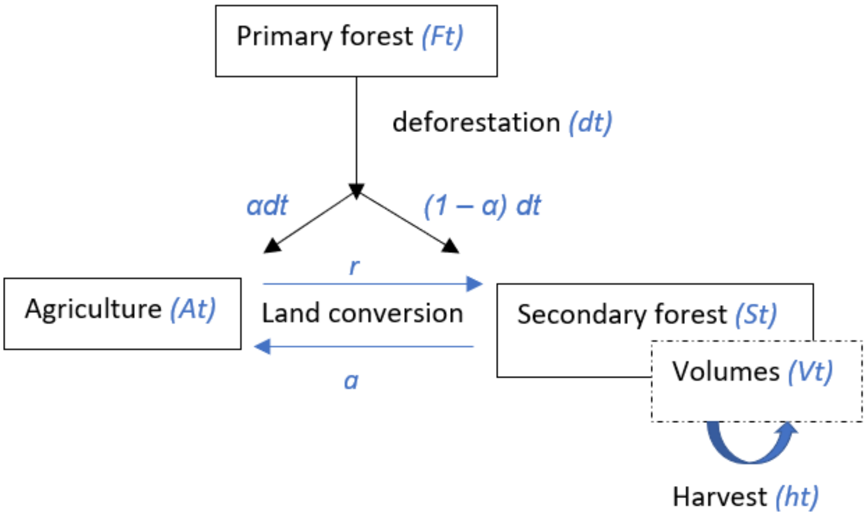


Fig. 1 Representation of the concepts and land use dynamics in the model

grow logistically according to the equation :

$$\dot{V_t} = \gamma \; V_t \; (1 - \frac{V_t}{S_t K}) - h_t * \frac{V_t}{S_t} \tag{4}$$

where γ is the intrinsic growth rate of forest, K is the carrying capacity of a unit area of forest, and h_t is the area (in hectares) of secondary forest harvested. To avoid scaling issues and ensure that all variables are expressed in consistent units, we multiply h_t by $\frac{V_t}{S_t}$, a volume-per-hectare ratio. The total capacity of forest volume or effective carrying capacity of the entire forested area scales with the area of secondary forest in the landscape.

Net social welfare arises from the use and non-use benefits and costs from all three land use types. Primary forest generates non-timber benefits arising from ecosystem services (denoted by the function $B_e(F_t)$), as well as wood benefits from harvested volumes. Non-wood benefits include those generated by ecosystem services, such as those from regulating or supporting ecosystem services (soil retention, water purification and flood control), cultural services (aesthetic or spiritual value), or the myriad of benefits from biodiversity preservation [40]. Non-wood benefits increase with the area of primary forest but at a diminishing rate ($\frac{\partial B_e}{\partial F_t} > 0$ and $\frac{\partial^2 B_e}{\partial^2 F_t} < 0$). This implies that the additional benefits gained from each extra unit of primary forest decrease with larger forests. For example, [41] emphasizes that the economic value of ecosystem services is closely linked to accessibility, with benefits decreasing as travel costs rise.

We suppose that primary forest exists at a constant density, and thus each unit area deforested yields a specific volume of usable timber. Harvesting primary forests incurs a convex cost of deforestation $C_d(d_t)$. When the land planner harvests primary forest to convert it to agriculture or secondary forest, s/he incurs conversion costs given by $C_a(a_t)$ and $C_r(r_t)$ respectively. Conversion costs are convex, as we consider homogeneous land, the preferences for each use depends on the relative rental rate in the initial data. We assume that when wood is harvested, it is clear cut and sold on the market, obtaining benefits for wood from deforestation of primary forest (d_t) and harvest from secondary forest (h_t) according to the functions $B_{w1}(d_t)$ and $B_{w2}(h_t)$ respectively. For simplicity, we consider timber from primary and secondary forests are homogeneous products (e.g., they have the same price). Harvest costs in secondary forest are given by the convex function $C_h(h_t)$. Finally, agriculture generates land rents according to the function $B_A(A_t)$, where $B_A(A_t)$ is a linear function.

Thus, the land planner chooses the land use allocation of primary forest, secondary forest, and agriculture, as well as the harvest of secondary forest, to maximize discounted net social welfare according to the maximization problem :

$$\begin{aligned}\max_{d_t,r_t,a_t,h_t} \quad W = \int_0^{\infty} \big[&B_e(F_t) + B_A(A_t) + B_{w1}(d_t) + B_{w2}(S_t, V_t, h_t) \\ &- C_d(d_t) - C_r(r_t) - C_h(S_t, V_t, h_t) - C_a(a_t)\big] e^{-\delta t}\, dt\end{aligned}$$

subject to:

$$\begin{aligned}\dot{F}_t &= -d_t \\ \dot{A}_t &= \alpha\, d_t - r_t + a_t \\ \dot{S}_t &= (1-\alpha)\, d_t - a_t + r_t \\ \dot{V}_t &= \gamma\ V_t\ (1 - \frac{V_t}{S_t K}) - h_t * \frac{V_t}{S_t} \\ 0 &\le h_t \le S_t \\ r_t &\neq a_t \\ &F_0, A_0, S_0, V_0 \text{ given}\end{aligned} \tag{5}$$

where δ is the discount rate, and F_0, A_0, S_0, and V_0 represent the initial proportions of primary forest, agriculture, secondary forest, and harvestable wood respectively.

2.2 Analytical solution

Following the program above and land user's problem, the current value of the Hamiltonian takes the form :

$$\begin{aligned}H = B_e\ (F_t) + B_A\ (A_t) + B_{w1}\ (d_t)\ + B_{w2}\ (S_t, V_t, h_t)\ - C_d(d_t) -\ C_r(r_t)\ - C_h(S_t, V_t, h_t)\ - C_a(a_t) \\ -\lambda_t d_t\ +\ \mu_t\ (\alpha d_t - r_t + a_t) + \phi_t\ (r_t - a_t + (1-\alpha)\ d_t) + \eta_t((\gamma\ V_t\ (1 - \frac{V_t}{SK})) - h_t * \frac{V_t}{S_t})\end{aligned} \tag{6}$$

where λ_t, μ_t, ϕ_t, and η_t are the co-state variables (shadow values) of extra units of primary forest, agriculture, secondary forest, and volume of harvestable timber.

The necessary first-order conditions are:

$$\frac{\partial H}{\partial d_t} = 0 \implies \lambda_t = \frac{\partial Bw_2}{\partial d_t} - \frac{\partial C_d}{\partial d_t} + \mu_t\ \alpha + \phi_t\ (1-\alpha) \tag{7}$$

$$\frac{\partial H}{\partial h_t} = 0 \implies \eta_t = (\frac{\partial Bw_1}{\partial h_t} - \frac{\partial C_h}{\partial h_t}) * \frac{S_t}{V_t} \tag{8}$$

$$\frac{\partial H}{\partial r_t} = 0 \implies \phi_t = \frac{\partial C_r}{\partial r_t} + \mu_t \tag{9}$$

$$\frac{\partial H}{\partial a_t} = 0 \implies \mu_t = \frac{\partial C_a}{\partial a_t} + \phi_t \tag{10}$$

Equation (7) tells us that the value of an extra unit of primary forest is equal to the marginal net benefits or opportunity costs of using the land for another purpose. The first set of terms is the direct net marginal benefits of deforestation; the second set is the marginal benefits of a unit of deforested land allocated to agriculture or secondary forest. Equation (8) shows that the value of an extra unit of harvestable timber is equal to marginal net benefits of harvesting secondary forest scaled by the ratio of secondary forest area and volume. Equations (9) and (10) indicate that the values of an extra unit of secondary forest and agriculture scale with the implicit benefits of the other land use type (an opportunity cost) minus the marginal costs of land conversion.

The adjoint equations are given by,

$$\dot{\lambda} - \delta\lambda = -\frac{\partial B_e}{\partial F_t} \tag{11}$$

$$\dot{\eta} - \delta\eta = -[\frac{\partial Bw_1}{\partial V_t} - \frac{\partial C_h}{\partial V_t} + \eta\gamma - \frac{2\eta\gamma V}{SK} - \frac{\eta h_t}{S_t}] \tag{12}$$

$$\dot{\phi} - \delta\phi = -[\frac{\partial Bw_1}{\partial S_t} - \frac{\partial C_h}{\partial S_t} + \frac{\eta\gamma}{K}(\frac{V}{S})^2 + \frac{h\eta V}{S^2}] \tag{13}$$

$$\dot{\mu} - \delta\mu = -\frac{\partial B_A}{\partial A_t} \tag{14}$$

Re-arranging equations (11)-(14) provides the equations of motion of the shadow values for each state variable, the values of which are governed by the difference between marginal costs and benefits, plus the discounted current value of each costate variable.

We adopt the methodology of Fenichel et al. (2010), Fenichel et al. (2015), Horan and Fenichel (2007), and Horan et al. (2011) to solve for the optimal paths of land conversion and secondary forest harvest. In short, the method involves taking a series of time derivatives of the necessary first order conditions, setting them equal to the adjoint equations, and solving for the equations of motion for the control variables. A detailed step-by-step guide of the process can be found in the Appendix.

Changes in deforestation, land conversion to agriculture and secondary forest, and secondary forest harvest are governed by the equations:

$$\dot{d} = \frac{-\frac{\partial B_e}{\partial F_t} + \delta\lambda - \alpha_0\ (-\frac{\partial B_A}{\partial A_t} + \delta\mu) - (1-\alpha_0)\ (-\frac{\partial Bw_1}{\partial S_t} + \frac{\partial C_h}{\partial S_t} - \frac{\eta\gamma}{K}(\frac{V}{S})^2 - \frac{h\eta V}{S^2} + \delta\phi)}{\frac{\partial^2 Bw_2}{\partial^2 d} - \frac{\partial^2 C_d}{\partial^2 d}} \tag{15}$$

$$\dot{a} = \frac{-\frac{\partial B_A}{\partial A_t} + \delta\mu + \frac{\partial Bw_1}{\partial S_t} - \frac{\partial C_h}{\partial S_t} + \frac{\eta\gamma}{K}(\frac{V}{S})^2 + \frac{h\eta V}{S^2} - \delta\phi}{\frac{\partial^2 C_a}{\partial^2 a}} \tag{16}$$

$$\dot{r} = \frac{-\frac{\partial Bw_1}{\partial S_t} + \frac{\partial C_h}{\partial S_t} - \frac{\eta\gamma}{K}(\frac{V}{S})^2 - \frac{h\eta V}{S^2} + \delta\phi + \frac{\partial B_A}{\partial A_t} - \delta\mu}{\frac{\partial^2 C_r}{\partial^2 r}} \tag{17}$$

$$\dot{h} = \left[\frac{-\frac{\partial Bw_1}{\partial V_t} + \frac{\partial C_h}{\partial V_t} - \eta\gamma + \frac{2\eta\gamma V}{SK} + \frac{\eta h_t}{S_t} + \delta\eta}{\frac{\dot{S}V - S\dot{V}}{V^2}} + \dot{V}\left(-\frac{\partial^2 Bw_1}{\partial h \partial V} + \frac{\partial^2 C_h}{\partial h \partial V}\right)\right.$$
$$\left. + \dot{S}\left(-\frac{\partial^2 Bw_1}{\partial h \partial S} + \frac{\partial^2 C_h}{\partial h \partial S}\right)\right] \times \frac{1}{\frac{\partial^2 Bw_1}{\partial^2 h} - \frac{\partial^2 C_h}{\partial^2 h}} \tag{18}$$

These equations represent the evolution of the control variables over time as a function of the state variables and model parameters. They include the future benefits that are sacrificed when altering a state variable today, as well as the opportunity costs of not allocating land to an alternative use. Together with equations (7)-(10) and (11)-(14), these form a complete system of ordinary differential equations to describe the behavior of all state, co-state, and control variables in the model.

Furthermore, we quantified the marginal rates of substitution of harvest intensity and forest area in the long term, which is equal to: $\frac{\frac{\partial bw_2}{\partial h_t}}{\frac{\partial bw_2}{\partial S_t}}$. Intuitively, this value represents the amount of compensation in harvest for a change in the area of secondary forest to maintain a given level of benefits of wood production. Similarly, we calculate the marginal rate of substitution between primary forest and secondary forest, which equals $\frac{\frac{\partial b_e}{\partial F_t}}{\frac{\partial bw_2}{\partial S_t}}$. In each case, we substitute the state variables by their steady state values.

Note that the equations for the co-state and control variables are in their general forms and are not restricted to a particular functional form. However, due to the complexity of the model and the inter-connectedness of the land use allocations, we were unable to solve for a closed-form solution. Therefore, we turn to numerical methods to explore the behavior of the model under different scenarios of management policy.

2.3 Numerical analysis

2.3.1 baseline scenarios and parameters

We set the model parameters to represent fictional regions. We do so for two reasons. First, we want to avoid any misinterpretations of our paper as a policy analysis and our results as normative. And second, while we would prefer to calibrate the model to realistic data, unfortunately, we lack reliable estimates of many of the benefit and cost parameters. Therefore, the model parameters are defined according to the literature (where available) and then by what makes sense in the model. A summary of coefficients and their corresponding values can be found in Table 1. For clarity purposes we normalize the land uses to one for the presentation of the results.

Across our model scenarios, we will compare two separate regions differing only in their initial land allocations. Region A comprises 10.42% of primary forest, 35% of secondary plantation forests, and 54% as designated agricultural land. Initial timber volumes of secondary forest are 5078.330 M m^3. Region A can be viewed as a developed country or region in the later stages of forest transition, where primary forests have already been depleted during the early phase of the transition (such as the 27 countries in the FAO's EU-27 classification). Region B is comprised of 32% primary forest area, 2.25% secondary forest area, and 65% agriculture. Initial timber volumes of secondary forest are also 5078.33 M m^3. This region can be compared to a developing country nearing the forest transition's turning point, with large areas of both agricultural land and primary forest (such as a country in South America).

Our baseline parameters, which we use as a comparison point for the other scenarios in our study, are found in Table 2. We then simulate three scenarios to represent expected changes in wood demand due to increasing environmental and political pressures on forest resources and climate change. The first scenario, ”increased timber demand,” involves a fourfold increase in the benefits of timber harvest (price). This scenario reflects the anticipated rise in timber demand driven by bioenergy and bioeconomy policies, such as the Renewable Energy Directive or the EU Bioeconomy Strategy. The second scenario, ”forest conservation policy,” builds on the increased timber demand scenario by raising the multiplier of deforestation costs by a factor of five in addition to increased timber demand. This scenario aligns with recent policies focused on forest conservation and restoration, such as the EU Forest Strategy for 2030 and the EU Deforestation Regulation. Lastly, we introduce a ”secondary forest tree mortality” scenario, where the growth rate of forest density (γ) is reduced from 0.9 to 0.4, while maintaining increased timber demand. This change accounts for the impact of intensifying droughts, a consequence of climate change, which causes increased tree mortality and reduced forest productivity [42, 43].

2.3.2 Sensitivity and steady-state analysis

In order to identify the key parameters and test the robustness of the model, we conducted a sensitivity analysis that involves systematically changing one parameter at a time while keeping the others constant. We used the initial values from region B to run the analysis, varying the model parameters by 1%, 5%, and 10%. After adjusting the parameters, we compared the results in the long term (the steady state) with the baseline model with our original parameter values (Table 1). We then calculated the mean percentage change in both state and control variables.

Specifically, we vary the following parameters: secondary forest carrying capacity (K), secondary forest growth rate (γ), discount rate (δ), the multiplier of environmental benefits (be_1), the power of environmental benefits (be_2), the multiplier of timber benefits from primary forest (bw_1), the multiplier of timber benefits from secondary forest (bw_2), the power of timber benefits (bw_3), the multiplier of agricultural benefits (ba_1), the power of agricultural benefits (ba_2), the multiplier of deforestation costs (cd_1), the power of deforestation costs (cd_2), the multiplier of secondary forest harvesting costs (ch_1), the power of secondary forest harvesting costs (ch_2), the multiplier of reforestation costs (cr_1), the power of reforestation costs (cr_2), the multiplier of agricultural costs (ca_1) and the power of agricultural costs (ca_2).

2.3.3 Solver settings and software

We solve the model as a nonlinear dynamic continuous problem in Julia with the *Ipopt* (interior-point-OPtimizer) solver. Technically speaking, the solver requires the problem to be solved with fixed terminal conditions. We calibrated the terminal time conditions to be near the long term steady state values, and then ran the model long enough to stabilize at those values before being constrained to arrive at the terminal endpoint, effectively resulting in free endpoint problem. *Ipopt* uses a line search technique along with a filter that ensures the solution remains feasible (maximizes the objective function) and stays within the constraints of the model while making progress towards an optimal solution. It runs sets of candidate trajectories and stores a set of candidates solution based on the values of their objective function and violation of constraints. Finally, it filters out solutions that do not provide sufficient improvement, including a criteria related to the step size (solvability). We use *infiniteOpt* package, which is designed to facilitate the automatic transcription of infinite-dimensional optimization problems (e.g. variables in continuous time) to be solvable model in a discrete approach. Details on the outputs of optimization for both regions are given in section 8 of Supplementary Material.

Functions

Name	Function
Environmental benefits	$be_1 \cdot (F)^{be_2}$
Agricultural benefits	$ba_1 \cdot (A)^{ba_2}$
Timber benefits 1	$bw_1 \cdot (d)^{bw_2}$
Timber benefits 2	$bw_1 \cdot (S, V, h)^{bw_2}$
Primary forest harvesting costs	$cd_1 \cdot (d)^{cd_2}$
Secondary forest harvesting costs	$ch_1 \cdot (S, V, h)^{ch_2}$
Secondary forest regeneration costs	$cr_1 \cdot (r)^{cr_2}$
Agricultural costs	$ca_1 \cdot (a)^{ca_2}$

Parameters

Coef	Interpretation	Value	Unit	Origin
be_1	Multiplier of the environmental benefits	969	€/ha	Costanza et al. 1997
ba_1	Multiplier of the agricultural benefits	823	\$/ha	FAO 2020
bw_1, bw_2	Multiplier of the timber benefits	569	\$/m^3	FAO 2020
cd_1	Multiplier of PF harvesting costs	10	\$/m^3	Assumed
cr_1	Multiplier of SF regeneration costs	10	\$/ha	Assumed
ca_1	Multiplier of agricultural costs	10	\$/ha	Assumed
ch_1	Multiplier of SF harvesting costs	50	\$/ha	Assumed
be_2	Power of the environmental benefit	1/2	—	Assumed
cd_2	Power of PF harvesting costs	2	—	Assumed
ch_2	Power of SF harvesting costs	1.1	—	Assumed
cr_2	Power of SF regeneration costs	1.1	—	Assumed
ca_2	Power of agricultural costs	1.1	—	Assumed
α	Fixed proportion of PF to agriculture	0.2	—	Assumed

Table 1 Functional forms (top) and values of coefficients (bottom) for each region. A double line separates the two sections.

3 Results

3.1 Baseline

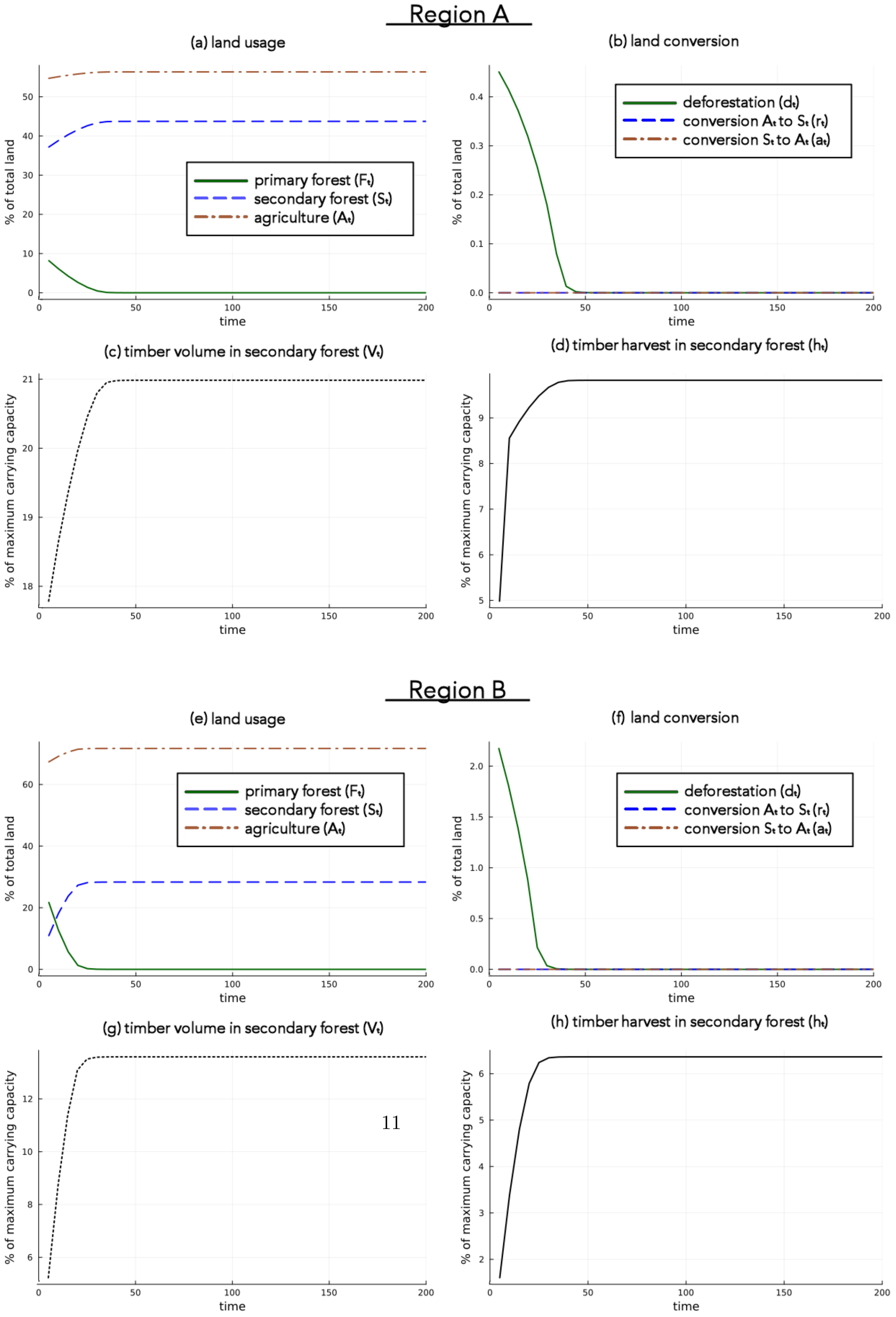


Fig. 2 Initial land allocation and secondary forest volumes in region A and B.

Figures summarizing our findings can be found in Figures 2-4. It is worth reminding the reader that, when comparing our scenarios to the baseline, we will be comparing their long term, steady state values.

In the baseline scenario, in both regions, the area of primary forest decreases rapidly at the beginning of the period to meet the demand for timber and agriculture, and then remains at a constant level around zero over time. The power and the multiplier of timber benefits overweight the environmental benefits. The land planner harvests the primary forest to gain benefits from timber and converts it to secondary forest and agricultural land to capitalize on the benefits of those two land uses.

In region A, there are limited changes in agricultural area, while in region B, agricultural land more steeply increases at the beginning of the simulation. This difference arises from the fact that region A has less available land for conversion due to its smaller initial primary forest area, and the available land is primarily converted into secondary forest. Therefore, from an economic perspective, the trade-off associated with using land for secondary forest is higher than the trade-off of using the land for agriculture. In other words, the opportunity cost of secondary forest outweighs the opportunity cost of agriculture. This is reflected in the marginal rate of substitution between secondary forest harvest intensity and forest area at steady state (2,14 for both regions), which is interpreted as the number of units to expand the forest area by to compensate for a one unit loss in harvested volumes to maintain the benefits constant. The marginal rate of substitution between primary and secondary forest equals 0.17 in region A and 0.04 in region B. In more general terms, region B requires lower compensation in secondary forest area to maintain the same level of benefits for a change in primary forest area, all else being equal.

3.1.1 Increased timber demand

Across both regions, higher timber demand boosts the benefits of wood production, outweighing the environmental advantages of preserving primary forests. An initial surge in timber demand causes a rise in wood extraction from primary forests, contributing to a faster decline in the primary forest area in both regions. Simultaneously, there is a faster increase in the establishment of agricultural land and, to a lesser extent, into secondary forest.

We observe greater rates of decline in region B. A higher initial abundance of primary forest and the lower opportunity cost of it drives higher forest conversion to secondary forest. Economically speaking, the benefits of additional timber production from secondary forest is high compared to the foregone environmental benefits of primary forest, leading to deforestation and conversion to secondary forest plantations. Once the secondary forest stock reaches a certain level, primary forest exploitation stabilizes as harvesting shifts to the secondary forest. In Figures 3 and 4, we see that at the beginning of the period, harvested volumes in the secondary forest are near zero. As the forest grows, harvesting volumes increase. In contrast, primary forest harvesting starts at high levels but declines over time as the secondary forest grows, eventually stabilizing at a constant level near zero. As primary forest is no longer available for harvesting, the land planner relies on secondary forests to meet the demand for wood. There is a potential substituability between primary and secondary forest, and between intensified harvesting in primary and secondary forest and secondary forest area expansion to respond to timber demand. The marginal substitution rate between harvested volumes and secondary forest area is the same as baseline. The marginal rate of substitution between primary and secondary forest areas is higher than in the baseline scenario (0.28 for region A and 0.08 for region B). This indicates that as more primary forest is harvested, a greater area of secondary forest is required as compensation.

3.1.2 Forest conservation policy

The "forest conservation policy" scenario results in a larger primary forest area compared to the baseline scenario in both regions. Because of higher cost of harvesting forest, the net benefits of timber production do not outweigh the net benefits of either agricultural production or environmental benefits of primary forest. In region A, secondary forest area is 6% lower than the baseline in the long term, and the agricultural area remains very low. In region B, 6.5% less land is converted to agriculture and 25% less land is converted to secondary forest compared to the baseline scenario. The land planner prioritizes the environmental benefits of primary forests, while slightly reducing the focus on timber activities. Finally, as expected, in both regions primary forest conservation leads primary forest deforestation to be near zero. Harvest intensity in secondary forests is lower than in the baseline in both regions. However, in region B, harvest intensity is lower than in region A. This is because region B allocates less land to secondary forest compared to region A. Here, there is a substituability between primary and secondary forest resources, as deforesting primary forest is overly costly and secondary forest harvest intensity increases to compensate. The marginal rate of substitution between harvest intensity of secondary forest and secondary forest area equals 1.713 in region A and 1.844 in region B. The marginal rate of substitution between primary and secondary forest equals 0.00076 in region A and 0.0004 in region B. In more general terms, both regions require lower compensation in secondary forest harvest intensity than in baseline as harvesting is intensified in the remaining secondary forest areas.

3.1.3 Higher tree mortality in secondary forest

In both regions, reducing secondary forest growth has very little impact on land allocation compared to the baseline. Moreover, the results are quite similar to the increased timber demand scenario, indicating that modifying growth rate of secondary forest volumes has minimal effect on land use changes and primarily influences harvest intensity. Harvested volumes are lower in the secondary forest tree mortality scenario compared to the baseline for both regions, with primary forest deforestation being higher than the baseline for both regions. This results in a reduction of primary forest area to compensate for the lower productivity of secondary forest due to tree mortality. In this case, primary forest and secondary forest are substituable resources, as secondary forest is constrained, harvest is lower but this is compensated by higher primary forest harvest. The marginal substitution rate between harvested volumes and secondary forest area is 3.350 for region A and 3.550 for region B. This rate is higher than the baseline because volume growth is low, meaning more area is needed to compensate for each unit of harvested volume.

3.1.4 Sensitivity analysis

In general, the model is robust to parameter values and initial conditions. With the exception of the volume of timber in secondary forests (V_t), whose equation of motion is more non-linear than the other state variables, we saw reasonable changes in the long term, steady-state values of our state variables or controls. For details on the results of the sensitivity analysis, see Table 7 of the Supplemental Material.

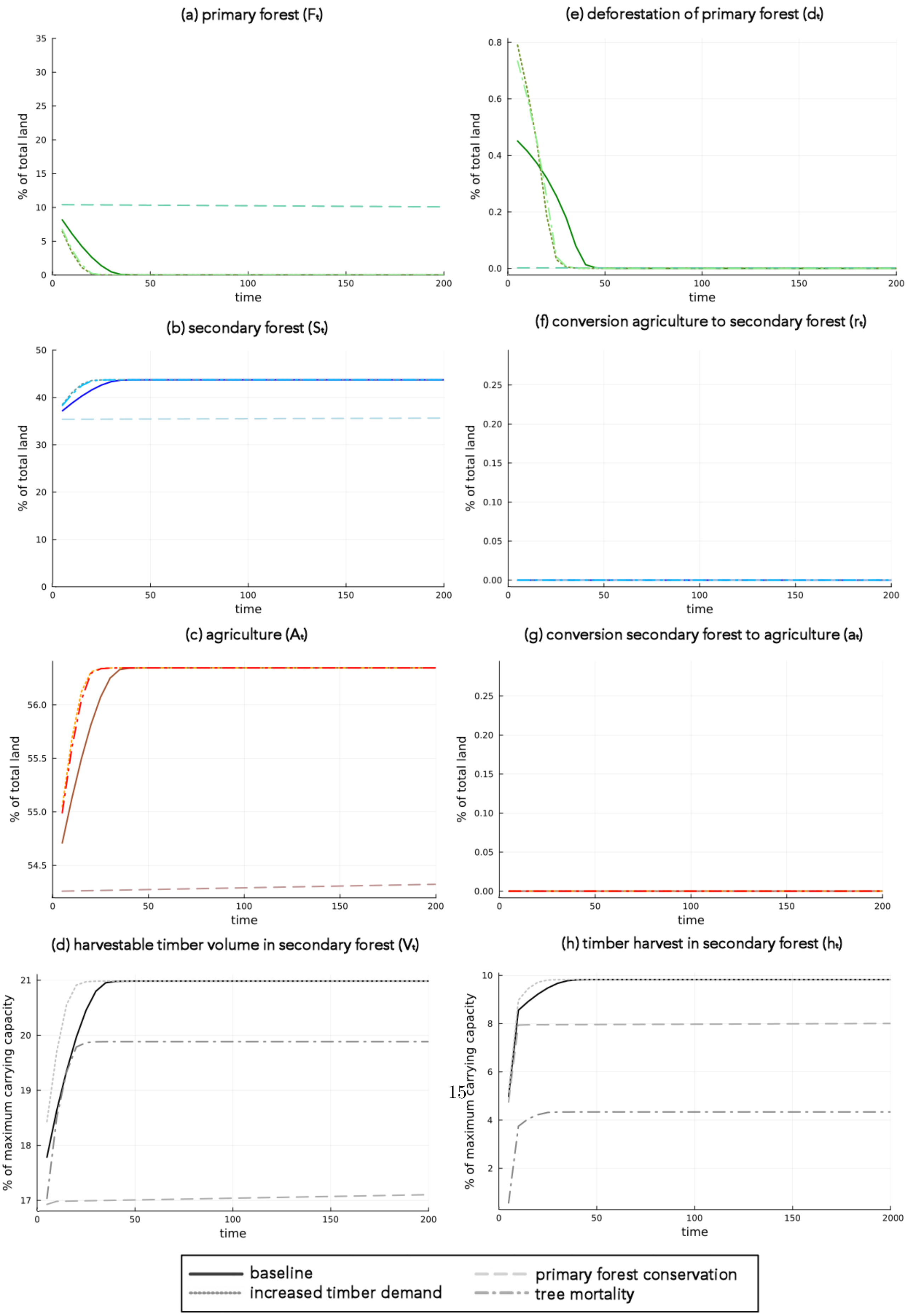
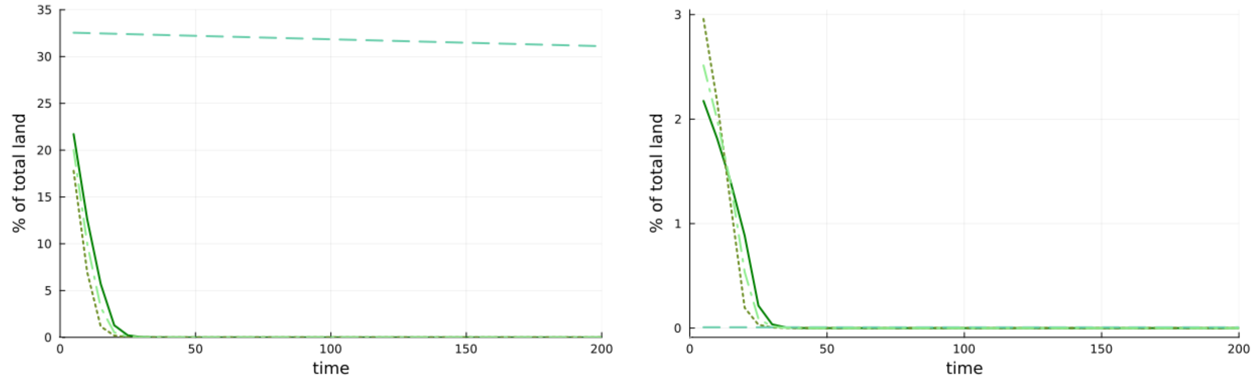
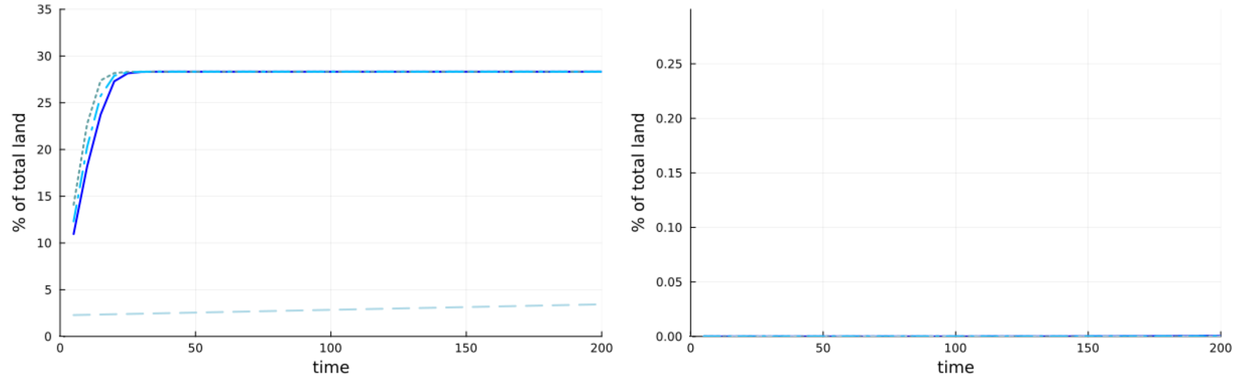


Fig. 3 Land allocation and harvested volumes under three scenarios for region A



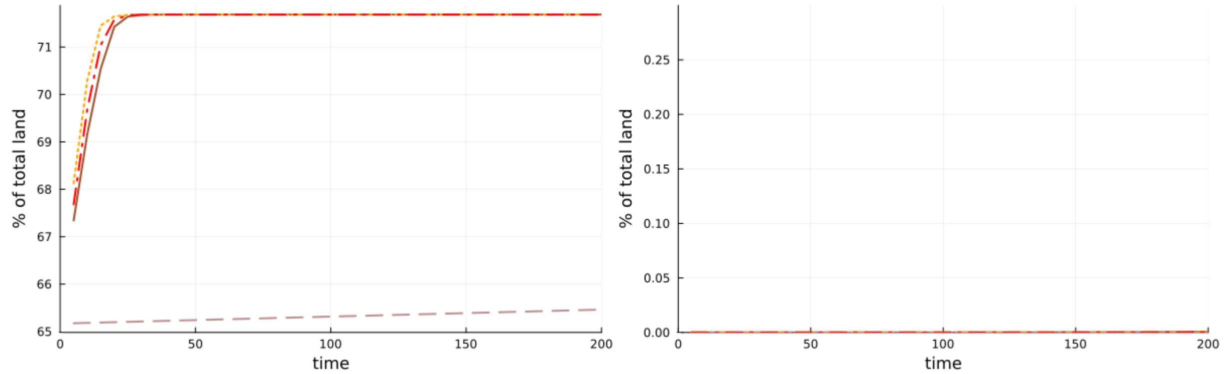
(a) primary forest (F_t)

(e) deforestation of primary forest (d_t)



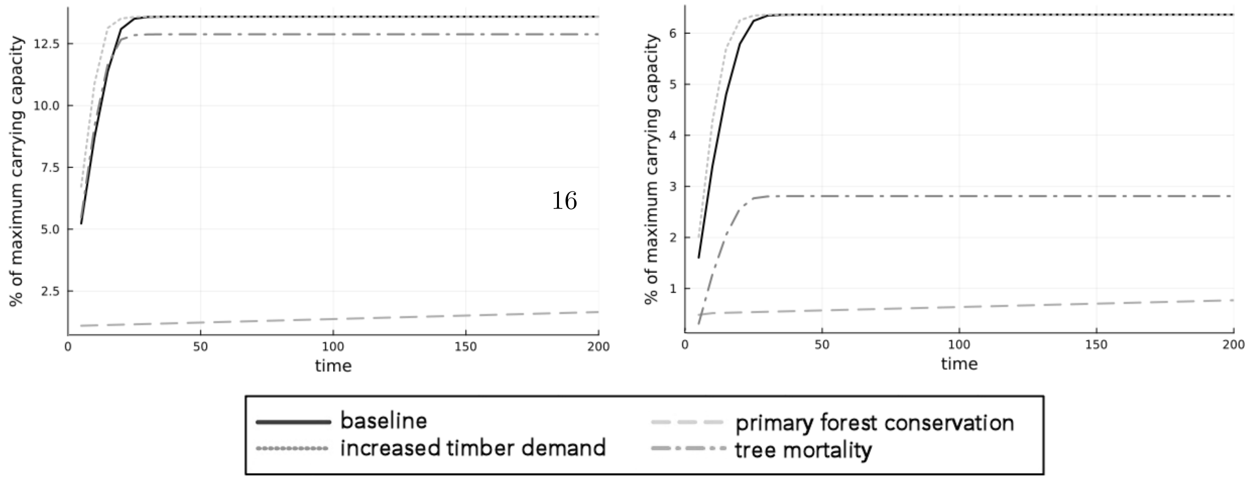
(b) secondary forest (S_t)

(f) conversion agriculture to secondary forest (r_t)



(c) agriculture (A_t)

(g) conversion secondary forest to agriculture (a_t)



(d) harvestable timber volume in secondary forest (V_t)

(h) timber harvest in secondary forest (h_t)

Fig. 4 Land allocation and harvested volumes under three scenarios for region B

4 Discussion

This study examines changes in forest management practices through land use allocation (including forest expansion) and forest harvest intensification. We simulate increasing wood demand, combined with conservation policies and tree mortality effects, to explore how forest management adapts to meet wood demand under different scenarios of public policy and climate change. How managers choose to allocate their land between primary and secondary forest and agriculture depends on the interplay between the costs and benefits of each land use and the harvest intensity of secondary forest. When there are fewer constraints on either resource, both intensified harvesting and forest expansion occur simultaneously. However, when one resource is costly (as in Scenarios 2 and 3), a degree of substituability emerges, not only between the two forest types but also between intensified harvesting and forest expansion.

Current forest conservation policies are often in conflict with the increasing demand for wood and wood products due to, for example, transitions to bioenergy [44]. For instance, strict logging restrictions in protected areas limit timber harvests [45], and reforestation regulations can delay access to new wood supplies [46]. While bans on clear-cutting in some regions are beneficial for providing habitat for biodiversity, they reduce the efficiency of wood production, which is necessary to meet growing demand in wood fiber [47]. Our results show increasing harvest intensity may not always mitigate the pressures on forest ecosystems, and in some cases, it may exacerbate deforestation rather than alleviate it [48]. The results of our first scenario indicate that increasing the marginal benefits of wood production can lead to forest allocation at both the extensive margin (e.g., deforestation, conversion of primary to secondary forests, and conversion of agricultural land to secondary forests) and the intensive margin (e.g., higher harvest rates in secondary forests). These changes can contribute to a decline in forest resources and the potential associated ecosystem services and carbon sinks.

Some studies support that jointly increasing harvest intensification and afforestation could be a desirable strategy for climate mitigation. In other words, wood harvest and climate mitigation are not mutually exclusive. For example, [35] modeled global forest carbon dynamics and found that combining increased harvest rates with expansive afforestation could provide a net carbon benefit, particularly when harvested wood products displace emissions-intensive materials like steel and concrete. Similarly, [49] analyzed forest carbon stocks in the southeastern United States. They found that higher demand for wood bioenergy could lead to both increased forest investments and land retention, thereby supporting long-term carbon storage. [50] argued that enhancements in forest growth through improved management, such as better silvicultural practices and fertilization, can increase biomass yield and carbon sequestration, especially when coupled with afforestation of previously non-forested lands. Forest management targeting climate mitigation can be facilitated by forest policies that ensure harvest levels remain below levels of forest growth and require regeneration after harvesting [51]. Indeed, we can observe cases of rising harvest intensity in concurrence with afforestation policies and higher carbon stocks [10], such as in Denmark [52] and the southeastern United States [53].

We illustrate in our second scenario, which included increased timber demand and primary forest conservation, that forest conservation and harvest are not mutually exclusive. We can still conserve primary and secondary forests while reasonably maintaining secondary forest harvest, through the magnitude of this result depends on initial conditions. In other words, primary and secondary forests act as substitutes for meeting timber demand. This connects well with other examples of substitutability in the resource economics literature, such as between ecosystem services or species conservation. Primary forest can be conserved with secondary forests being more heavily harvested, which could help to preserve key ecosystem services and carbon sinks inherent to primary forests. However, part of this result is influenced by how we modeled our forest conservation policy, particularly due to the high harvesting cost assigned to primary forests. For example, the current European Union directives for biodiversity conservation puts in place a goal of setting aside a minimum of 30% percent of land by 2030 for protected areas. In our model, this could be accounted for by a constraint in the quantity of primary or secondary forest that must be maintained at all times. While we would not expect this to change our main findings, it will affect the trajectories of the model to its long term equilibrium.

A recent European Commission report on the use of woody biomass for energy production suggested that requiring forest conservation in a system with high timber demand may not be efficient in the long term [54]. It is therefore essential to find the right policy balance that allows for the efficient production of woody biomass, optimizes greenhouse gas savings, and maintains ecosystem services, all without causing deforestation. They say this for two main reasons. First, intensive exploitation of soils and secondary forests can cause significant environmental damage. For instance, [55] found that intensive biomass harvesting could result in a substantial carbon transfer from forests to the atmosphere (142 to 497 Tg-C). Moreover, intensive harvesting practices can deplete nitrogen and phosphorus in the soil, thereby reducing soil fertility and forest productivity [56]. Second, afforestation or forest conservation policies shift deforestation and land use change to outside the country, an effect known as leakage or displacements. In a general equilibrium model, [57] estimated that countries may transfer 42 to 95% of their reduced forestry production elsewhere. Other recent studies also show that leakage can undermine forest conservation benefits [58–60]. Recent developments in sustainable forest management indicate that increasing harvest intensity should be accompanied by non-exploitable afforested areas to offset the carbon loss from intensive wood exploitation, including circular economies [61, 62].

Issues of sustainable forest management are further compounded by the effects of climate change, with extreme weather events such as drought, wind storms, and insect outbreaks occurring in increasing frequency and intensity in the future [63]. We model the consequences of this in our third scenario, which combines increased timber demand with higher tree mortality, and observe that mortality in secondary forests leads to greater harvesting of primary forests and conversion to agriculture, as secondary forest becomes less profitable. Environmentally, tree mortality reduces carbon sinks and biodiversity [43, 64]. Ecologically speaking, the effects of tree mortality are well documented. In soils, it can lead to increased erosion, altered albedo, and reduced carbon absorption [65]. For trees, drought and rising temperatures can cause increased evapotranspiration, soil and plant dehydration, and tree death [42]. This effect is further exacerbated by the accelerated depletion of primary forests, as both forest types may be used to meet timber demand. These findings highlight the need to strengthen forest resilience in order to address unsustainable patterns, (for example, through species diversification [66], assisted natural regeneration, or adaptive forest management [67]). There is limited research on the economic impacts of tree mortality. Future research should aim to fill this gap by developing land use or forest management models that incorporate the impacts of environmental conditions and climate risks on management decisions and carbon sinks.

However, when drawing conclusions from our results, it is important to note that our model is not without limitations. Like any model, our results are dependent on initial conditions and assumptions (see the Supplemental Material for a deeper discussion of this issue). Our sensitivity analysis shows that the model is relatively robust to changes in parameter values (and any differences are consistent with what we would expect from intuition), and certainly, the modeling framework can be extended. Our study does not consider the effects of climate change on agricultural production, which would influence crop yields and, as a consequence, land allocation to agriculture. Production choices available to forest owners can be very detailed, which may include species diversification, adjustments in thinning rates, or litter raking (among others). Moreover, there is a diverse set of indicators for measuring management intensity in addition to harvest quantity, such as tree species selection, rotation period, and forest density [9]. Future refinements could consider incorporating additional factors that might provide a more comprehensive assessment of environmental impacts. These might include other land-use transition costs (e.g., soil preparation, energy use) and indirect effects such as land displacement or carbon leakage associated with primary forest loss. We could envision extending the model, integrating variables related to environmental quality, carbon accounting, and international trade, as well as by introducing elements of risk and uncertainty, and temporal aspects of transitions (e.g., conversions take time).

Modeling land-use distribution through dynamic optimization control can offer valuable insights into the cost-effectiveness of different political strategies while taking into account the tradeoffs associated with climate change mitigation, forest conservation, and wood production [68]. Our scenarios represents potential win-win strategies by demonstrating the substituability between primary and secondary forests in fulfilling wood demand. Win-win policy approaches aim to meet the growing demand for wood without compromising forest resources [54]. Such strategies not only contribute to climate change mitigation but also supports the continued provision of forests' ecological, economic, and social benefits over the long term. However, the literature increasingly shows the importance of conservation in maintaining biodiversity, the flows of ecosystem services, and preservation of ecosystem functioning [12], the effective implementation of which requires a coordinated set of measures. Developing realistic compensation schemes for conservation is essential to incentivize stakeholder participation in forest protection, particularly when opportunity costs are high [69]. The identification of suitable land areas for conservation or restoration can aid ecological viability and cost-effectiveness [70]. Prioritizing ecologically valuable forest zones, such as areas with high biodiversity or carbon density, helps maximize conservation outcomes [71]. Lastly, the selection of appropriate restoration methods is critical for recovering ecosystem functions and enabling degraded lands to partially recover primary forest functions [72]. Together, these components support the design of conservation policies that are both environmentally effective and economically feasible, and will play a role in optimal management policies that maximize ecological and economic goals.

Primary forest and secondary forest areas are substitutable resources for wood production. Concerning management strategies, in some cases, harvest intensity and forest expansion strategies are used as complements, while in other cases, they act as substitutes. As wood demand increases, the profitability of wood production rises, resulting in a combination of deforestation and higher harvesting intensity. In this case, an increasing harvesting intensity strategy does not necessarily alleviate deforestation pressures. Shifts between expanding forest areas (extensive margin production) and increasing harvested volumes (intensification) occur only under specific constraints. For instance, when primary forest conservation measures are enforced, secondary forests experience higher harvesting intensity to meet the rising timber demand. Ultimately, the impact of tree mortality leads to a reduction in harvest in secondary forest and higher harvest in primary forest.

We suggest future research to focus on developing more optimal control land use and forest management models that incorporate the impacts of environmental conditions and climate risks or hazard on management decisions and carbon sinks.

References

[1] Gustavsson, L., Madlener, R., Hoen, H.-F., Jungmeier, G., Karjalainen, T., Klöhn, S., Mahapatra, K., Pohjola, J., Solberg, B., Spelter, H.: The role of wood material for greenhouse gas mitigation. Mitigation and adaptation strategies for global change **11**, 1097–1127 (2006)

[2] Canadell, J.G., Raupach, M.R.: Managing forests for climate change mitigation. Science **320**(5882), 1456–1457 (2008)

[3] Geng, A., Yang, H., Chen, J., Hong, Y.: Review of carbon storage function of harvested wood products and the potential of wood substitution in greenhouse gas mitigation. Forest Policy and Economics **85**, 192–200 (2017)

[4] Searchinger, T., Heimlich, R., Houghton, R.A., Dong, F., Elobeid, A., Fabiosa, J., Tokgoz, S., Hayes, D., Yu, T.-H.: Use of us croplands for biofuels increases greenhouse gases through emissions from land-use change. Science **319**(5867), 1238–1240 (2008)

[5] Miyake, S., Renouf, M., Peterson, A., McAlpine, C., Smith, C.: Land-use and environmental pressures resulting from current and future bioenergy crop expansion: A review. Journal of Rural Studies **28**(4), 650–658 (2012)

[6] Fayiga, A., Saha, U.: Effect of climate change on soil productivity in developing countries. Asian Journal of Environment & Ecology **4**(1), 1–22 (2017)

[7] Hardie, I.W., Parks, P.J., Kooten, G.C.: The economics of land use at the intensive and extensive margins. International Yearbook of Environmental & Resource Economics, 2003/2004 (2004)

[8] Kartodihardjo, H., Supriono, A.: The Impact of Sectoral Development on Natural Forest Conversion and Degradation: The Case of Timber and Tree Crop Plantations in Indonesia vol. 26. Center for International Forestry Research, ??? (2000)

[9] Erb, K.-H., Luyssaert, S., Meyfroidt, P., Pongratz, J., Don, A., Kloster, S., Kuemmerle, T., Fetzel, T., Fuchs, R., Herold, M., *et al.*: Land management: data availability and process understanding for global change studies. Global change biology **23**(2), 512–533 (2017)

[10] Naudts, K., Chen, Y., McGrath, M.J., Ryder, J., Valade, A., Otto, J., Luyssaert, S.: Europe's forest management did not mitigate climate warming. Science **351**(6273), 597–600 (2016)

[11] Duncker, P.S., Raulund-Rasmussen, K., Gundersen, P., Katzensteiner, K., De Jong, J., Ravn, H.P., Smith, M., Eckmüllner, O., Spiecker, H.: How forest management affects ecosystem services, including timber production and economic

return: synergies and trade-offs. Ecology and Society **17**(4) (2012)

[12] Brockerhoff, E.G., Barbaro, L., Castagneyrol, B., Forrester, D.I., Gardiner, B., González-Olabarria, J.R., Lyver, P.O., Meurisse, N., Oxbrough, A., Taki, H., et al.: Forest biodiversity, ecosystem functioning and the provision of ecosystem services. Springer (2017)

[13] Seydewitz, T., Pradhan, P., Landholm, D.M., Kropp, J.P.: Deforestation drivers across the tropics and their impacts on carbon stocks and ecosystem services. Anthropocene Science **2**(1), 81–92 (2023)

[14] Sunderland, T.C., Rowland, D.: Forests, land use, and challenges to climate stability and food security. In: Sustainable Food and Agriculture, pp. 95–116. Elsevier, ??? (2019)

[15] Mather, A.S.: The forest transition. Area, 367–379 (1992)

[16] Rudel, T.K., Schneider, L., Uriarte, M.: Forest transitions: An introduction. Land use policy **27**(2), 95–97 (2010)

[17] Tandetzki, J., Köthke, M., Schier, F., Weimar, H.: A systematic review of forest area development drivers estimated under the concepts of environmental kuznets curve and forest transition hypothesis. Environmental Research Letters (2024)

[18] Tandetzki, J., Schier, F., Köthke, M., Weimar, H.: An evidence and gap map of the environmental kuznets curve and the forest transition hypothesis for estimating forest area development. Environmental Research Letters **17**(12), 123005 (2022)

[19] Rudel, T.K., Coomes, O.T., Moran, E., Achard, F., Angelsen, A., Xu, J., Lambin, E.: Forest transitions: towards a global understanding of land use change. Global environmental change **15**(1), 23–31 (2005)

[20] Mather, A.S., Needle, C.: The forest transition: a theoretical basis. Area **30**(2), 117–124 (1998)

[21] Barbier, E.B., Burgess, J.C., Grainger, A.: The forest transition: Towards a more comprehensive theoretical framework. Land use policy **27**(2), 98–107 (2010)

[22] Wolfersberger, J., Amacher, G.S., Delacote, P., Dragicevic, A.: The dynamics of deforestation and reforestation in a developing economy. Environment and Development Economics **27**(3), 272–293 (2022)

[23] Conrad, J.: Resource Economics. Cambridge University Press, Cambridge (1999)

[24] Hartman, R.: The harvesting decision when a standing forest has value. Economic Inquiry **14**(1), 52–58 (1976) https://doi.org/10.1111/j.1465-7295.1976.tb00377.x

[25] Van Kooten, G.C., Binkley, C.S., Delcourt, G.: Effect of carbon taxes and subsidies on optimal forest rotation age and supply of carbon services. In: Economics of Forestry, pp. 363–372. Routledge, London (2018)

[26] Chang, S.J.: Determination of the optimal rotation age: a theoretical analysis. Forest ecology and management **8**(2), 137–147 (1984)

[27] Reed, W.J.: The effects of the risk of fire on the optimal rotation of a forest. Journal of environmental economics and management **11**(2), 180–190 (1984)

[28] Rakotoarison, H., Loisel, P.: The faustmann model under storm risk and price uncertainty: A case study of european beech in northwestern france. Forest Policy and Economics **81**, 30–37 (2017)

[29] Caurla, S., Delacote, P.: Ffsm: un modèle de la filière forêts-bois française qui prend en compte les enjeux forestiers dans la lutte contre le changement climatique. INRA Sciences Sociales **2012** (2013)

[30] Rivière, M., Caurla, S.: Representations of the forest sector in economic models. Œconomia. History, Methodology, Philosophy (10-3), 521–553 (2020)

[31] Lobianco, A., Caurla, S., Delacote, P., Barkaoui, A.: Carbon mitigation potential of the french forest sector under threat of combined physical and market impacts due to climate change. Journal of Forest Economics **23**, 4–26 (2016)

[32] Sohngen, B., Mendelsohn, R., Sedjo, R.: Forest management, conservation, and global timber markets. American Journal of Agricultural Economics **81**(1), 1–13 (1999)

[33] Weyant, J.: Some contributions of integrated assessment models of global climate change. Review of Environmental Economics and Policy (2017)

[34] Favero, A., Mendelsohn, R., Sohngen, B.: Using forests for climate mitigation: sequester carbon or produce woody biomass? Climatic Change **144**, 195–206 (2017)

[35] Favero, A., Daigneault, A., Sohngen, B.: Forests: Carbon sequestration, biomass energy, or both? Science advances **6**(13), 6792 (2020)

[36] Favero, A., Baker, J., Sohngen, B., Daigneault, A.: Economic factors influence net carbon emissions of forest bioenergy expansion. Communications Earth & Environment **4**(1), 41 (2023)

[37] Wise, M., Calvin, K., Kyle, P., Luckow, P., Edmonds, J.: Economic and physical modeling of land use in gcam 3.0 and an application to agricultural productivity, land, and terrestrial carbon. Climate Change Economics **5**(02), 1450003 (2014)

[38] Calvin, K., Patel, P., Clarke, L., Asrar, G., Bond-Lamberty, B., Cui, R.Y.,

Di Vittorio, A., Dorheim, K., Edmonds, J., Hartin, C., *et al.*: Gcam v5. 1: representing the linkages between energy, water, land, climate, and economic systems. Geoscientific Model Development **12**(2), 677–698 (2019)

[39] Ermolieva, T.Y., Ermoliev, Y.M., Havlik, P., Mosnier, A., Leclere, D., Kraksner, F., Khabarov, N., Obersteiner, M.: Systems analysis of robust strategic decisions to plan secure food, energy, and water provision based on the stochastic globiom model. Cybernetics and systems analysis **51**, 125–133 (2015)

[40] Reid, W.V.: Millennium ecosystem assessment: Ecosystems and human well-being. mea (2005)

[41] Nghiem, T., Sunderland, T., Koh, L.: Economic valuation of ecosystem services fails to capture biodiversity value of tropical forests. Biological Conservation **178**, 163–170 (2014)

[42] Choat, B., Brodribb, T.J., Brodersen, C.R., Duursma, R.A., López, R., Medlyn, B.E.: Triggers of tree mortality under drought. Nature **558**(7711), 531–539 (2018)

[43] Wang, W., Peng, C., Kneeshaw, D.D., Larocque, G.R., Luo, Z.: Drought-induced tree mortality: ecological consequences, causes, and modeling. Environmental Reviews **20**, 109–121 (2012)

[44] Searchinger, T.D., Beringer, T., Holtsmark, B., Kammen, D.M., Lambin, E.F., Lucht, W., Raven, P., Ypersele, J.-P.: Europe's renewable energy directive poised to harm global forests. Nature communications **9**(1), 3741 (2018)

[45] Putz, F.E., Zuidema, P.A., Synnott, T., Peña-Claros, M., Pinard, M.A., Sheil, D., Vanclay, J.K., Sist, P., Gourlet-Fleury, S., Griscom, B., *et al.*: Sustaining conservation values in selectively logged tropical forests: the attained and the attainable. Conservation letters **5**(4), 296–303 (2012)

[46] Zhang, D.: Economics of reforestation and afforestation. In: Oxford Research Encyclopedia of Environmental Science. Oxford university press, ??? (2017)

[47] Keenan, R.J., Kimmins, J.: The ecological effects of clear-cutting. Environmental Reviews **1**(2), 121–144 (1993)

[48] Pirard, R., Dal Secco, L., Warman, R.: Do timber plantations contribute to forest conservation? Environmental Science and Policy (2016)

[49] Abt, K.L., Abt, R.C., Galik, C.: Effect of bioenergy demands and supply response on markets, carbon, and land use. Forest Science **58**(5), 523–539 (2012)

[50] Kauppi, P.E., Ciais, P., Högberg, P., Nordin, A., Lappi, J., Lundmark, T., Wernick, I.K.: Carbon benefits from forest transitions promoting biomass expansions and thickening. Global Change Biology **26**(10), 5365–5370 (2020)

[51] Eriksson, M., Samuelson, L., Jägrud, L., Mattsson, E., Celander, T., Malmer, A., Bengtsson, K., Johansson, O., Schaaf, N., Svending, O., *et al.*: Water, forests, people: the swedish experience in building resilient landscapes. Environmental Management **62**, 45–57 (2018)

[52] Nordlund, A., Westin, K.: Forest values and forest management attitudes among private forest owners in sweden. Forests **2**(1), 30–50 (2010)

[53] Aguilar, F.X., Mirzaee, A., McGarvey, R.G., Shifley, S.R., Burtraw, D.: Expansion of us wood pellet industry points to positive trends but the need for continued monitoring. Scientific reports **10**(1), 18607 (2020)

[54] Camia, A., Giuntoli, J., Jonsson, K., Robert, N., CazzanigaA, N., Jasinevičius, G., Avitabile, V., Grassi, G., Barredo, C., Mubareka, S., *et al.*: The Use of Woody Biomass for Energy Production in the EU. The EU commission, ??? (2021)

[55] Achat, D.L., Fortin, M., Landmann, G., Ringeval, B., Augusto, L.: Forest soil carbon is threatened by intensive biomass harvesting. Scientific reports **5**(1), 15991 (2015)

[56] Hume, A.M., Chen, H.Y., Taylor, A.R.: Intensive forest harvesting increases susceptibility of northern forest soils to carbon, nitrogen and phosphorus loss. Journal of Applied Ecology **55**(1), 246–255 (2018)

[57] Gan, J., McCarl, B.A.: Measuring transnational leakage of forest conservation. Ecological Economics **64**(2), 423–432 (2007)

[58] Ford, S.A., Jepsen, M.R., Kingston, N., Lewis, E., Brooks, T.M., MacSharry, B., Mertz, O.: Deforestation leakage undermines conservation value of tropical and subtropical forest protected areas. Global Ecology and Biogeography **29**(11), 2014–2024 (2020)

[59] Pendrill, F., Persson, U.M., Godar, J., Kastner, T., Moran, D., Schmidt, S., Wood, R.: Agricultural and forestry trade drives large share of tropical deforestation emissions. Global environmental change **56**, 1–10 (2019)

[60] Dou, Y., Da Silva, R.F.B., Yang, H., Liu, J.: Spillover effect offsets the conservation effort in the amazon. Journal of Geographical Sciences **28**, 1715–1732 (2018)

[61] Miassi, Y.E., Gélinas, N., Dossa, K.F.: The circular economy: A lever for the sustainable development of the wood and forestry sector in west africa. Forests **16**(3), 508 (2025)

[62] Yuniati, D., Nurrochmat, D.R., Pribadi, D.O., Djaenudin, R.D., Kuncahyo, B., Khotimah, H.: Unlocking economic growth: Circular bioeconomy implementation and the role of forestry industry. In: BIO Web of Conferences, vol. 123, p. 03003

(2024). EDP Sciences

[63] Seidl, R., Thom, D., Kautz, M., Martin-Benito, D., Peltoniemi, M., Vacchiano, G., Wild, J., Ascoli, D., Petr, M., Honkaniemi, J., *et al.*: Forest disturbances under climate change. Nature climate change **7**(6), 395–402 (2017)

[64] Martin, P.A., Newton, A.C., Cantarello, E., Evans, P.: Stand dieback and collapse in a temperate forest and its impact on forest structure and biodiversity. Forest Ecology and Management **358**, 130–138 (2015)

[65] Anderegg, W.R., Kane, J.M., Anderegg, L.D.: Consequences of widespread tree mortality triggered by drought and temperature stress. Nature climate change **3**(1), 30–36 (2013)

[66] Dymond, C.C., Tedder, S., Spittlehouse, D.L., Raymer, B., Hopkins, K., McCallion, K., Sandland, J.: Diversifying managed forests to increase resilience. Canadian Journal of Forest Research **44**(10), 1196–1205 (2014)

[67] Spathelf, P., Stanturf, J., Kleine, M., Jandl, R., Chiatante, D., Bolte, A.: Adaptive measures: integrating adaptive forest management and forest landscape restoration. Annals of Forest Science **75**, 1–6 (2018)

[68] Knoke, T., Hahn, A.: Global change and the role of forests in future land-use systems. Developments in environmental science **13**, 569–588 (2013)

[69] Busch, J., Lubowski, R.N., Godoy, F., Steininger, M., Yusuf, A.A., Austin, K., Hewson, J., Juhn, D., Farid, M., Boltz, F.: Structuring economic incentives to reduce emissions from deforestation within indonesia. Proceedings of the National Academy of Sciences **109**(4), 1062–1067 (2012)

[70] Strassburg, B.B., Rodrigues, A.S., Gusti, M., Balmford, A., Fritz, S., Obersteiner, M., Kerry Turner, R., Brooks, T.M.: Impacts of incentives to reduce emissions from deforestation on global species extinctions. Nature Climate Change **2**(5), 350–355 (2012)

[71] Margules, C., Pressey, R.: Systematic conservation planning. Nature (2000)

[72] Chazdon, R.L.: Beyond deforestation: restoring forests and ecosystem services on degraded lands. Science **320**(5882), 1458–1460 (2008)

Supplementary information. This article has accompanying supplementary material file.

5 Statements & Declarations

This work was supported by a grant overseen by the French National Research Agency (ANR) as part of the “Investissements d’Avenir” program (ANR-11-LABX-0002-01, Lab of Excellence ARBRE), and CLIMAE metaprogram. The authors would like to express their gratitude to Miguel Riviere for his valuable insights and feedback during the course of this study. The authors have no relevant financial or non-financial interests to disclose. All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Charis Anais Kanellos, David Shanafelt and Antonello Lobianco. The first draft of the manuscript was written by Charis Anais Kanellos and David Shanafelt. Reviewing and editing were performed by Philippe Delacote and David Shanafelt. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.