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Stability and resilience of a forest bio-economic equilibrium under natural disturbances

Félix Bastit*, David W. Shanafelt†, Marielle Brunette‡

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Abstract

Natural disturbances play a key role in the long-term evolution of a forest but are by essence unforeseeable. If a sustainable management is fixed in a forest, where the harvest is equal to the forest growth (such as at maximal sustainable yield), natural disturbances could jeopardise the established equilibrium by modifying the future forest growth and possibility to harvest timber. This paper aims at studying the stability of a bio-economic equilibrium, where a forest is first managed in a sustainable way and has reached an equilibrium between the timber market and biological timber production. So far in forestry, sustainable management schemes do not appropriately integrate disturbance regimes. To overcome this issue, we describe a bio-economic equilibrium that includes a forest inventory, a local unregulated timber market (whose variations are defined by an equilibrium-displacement model), and natural disturbances. The paper investigates the short- and long-term effects following a disturbances. For reasonable descriptions of both forest evolution and timber market equilibrium, we show that there exists a critical forest inventory under which it is impossible to find a stable state where the forest inventory persists in the long term. For a forest inventory larger than this critical level, the equilibrium is what we call "meta-stable", because while the forest inventory does often persist in the long term, there always exists a certain level of natural disturbance able to destabilize the equilibrium and, ultimately, exhaust the forest inventory. However, this threshold is often too large to threaten real forests. Finally, we derive the maximum frequency between hazards that ensures the long-term sustainability of the forest.

Keywords: multi-risk, sustainable management, economics, local timber market, forest.

JEL codes: D81 (Criteria for Decision-Making under Risk and Uncertainty); Q23 (Forestry); Q54 (Climate • Natural Disasters and Their Management • Global Warming)

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1 Introduction

The long-term sustainability of forest resources - defined as the maintainable harvest of timber (Hahn and Knoke, 2010) - is one of the driving problems of the forest sector, now and into the future (FAO, 2020). Indeed, forests are a key source of ecosystem services such as carbon storage, timber and non-timber products, biodiversity or water protection (FAO, 2020) and their continued maintenance is a real challenge. In this context, forest management, specifically timber harvest, constitutes a delicate bio-economic equilibrium between the renewable resource sold on a market and its natural production (Conrad and Clark, 1987; Conrad, 1999; Clark, 2010).

Such a bio-economic equilibrium is brittle because it is often disturbed by natural hazards such as windstorms, wildfires, or pest outbreaks. For instance, van Lierop et al. (2015) suggested that natural disturbances impact a mean surface area of 7.9 10^7 ha of forest each year worldwide, representing 1.9% of the 4.06 10^9 ha of the world's forests (FAO, 2020). At the European scale, Schelhaas et al. (2003) estimated that damages due to natural disturbances amounted to roughly 8% of harvested volumes during the second half of the 20^{th} century. Moreover, in a context of climate change, natural disturbances are expected to become more intense and more frequent (IPCC, 2012). Natural disturbances thus represent a threat for the permanence of the forest cover that can jeopardise the provisioning of ecosystem services, especially timber production. Moreover, occurrences of natural hazards can lead to increased volatility in timber markets (Gardiner et al., 2010), which can cause volatility in timber production as the quantity sold depends on its price (Brazee and Mendelsohn, 1988).

In this paper, we investigate how the quantity of timber in a forest evolves through time if timber is harvested and sold on a market, where hazards can have direct major impact on the level of the resource. We study the dynamics of a timber market, based on an equilibrium-displacement model including endogenous timber prices, facing large scale natural disturbance. Specifically, we address the following research questions. First, what are the conditions for a stable bio-economic equilibrium that balances timber demand and forest inventory growth, what are the main drivers of this equilibrium, and how sensitive is it to variations in these drivers? Next, if such an equilibrium is stable, what level of damages can a forest cope with and still maintain timber production? Finally, what is the impact of the frequency of natural hazards on the existence of such equilibrium?

This article is at the border of three branches of economics literature: first, empirical case studies from forest economics, especially developed after hurricane Hugo; second, the classical environmental economics literature; and lastly, theoretical forest economics linking the effect of price volatility on forest owners' decisions. First, on the empirical side, Prestemon and Holmes (2000) suggested that the main economic effect of a natural disturbance is a transfer of welfare between different forest owners. For example, forest owners impacted by storm hazards are forced to sell their timber at a reduced price because of the influx of wood on the market. After hurricane Hugo (USA), the timber price dropped by 49% in Florida while the inventory shock was as high as 21% (Kinnucan, 2016). This means that impacted forest owners sold their timber at a lower-than-expected price in the short term. However, in the long term, a higher price would be expected, because the quantity of timber in the forest is reduced, e.g. a scarcity of the resource (Conrad and Clark, 1987; Conrad, 1999; Clark, 2010). For hurricane Hugo, Prestemon and Holmes (2000) estimated this long-term effect to increase timber price by 15%. This means that forest owners who were not directly impacted could sell their timber at a higher price than expected in the long term, leading to a transfer of welfare between impacted and not impacted forest owners (Prestemon and Holmes, 2000). It is possible to calibrate a model from these econometrics analyses, but to the best of our knowledge, the question of the long-term dynamics of a forest facing natural disturbances from a theoretical point of view has yet not been tackled by the literature.

Second, the environmental economics literature includes examples of the management of natural resources under price volatility and natural disturbances, but seldom considers forests. Traditionally, the focus of this literature is optimal extraction of non-renewable resources (Hotelling, 1931; Coase, 1960) or the optimal management of renewable species stocks (Clark, 1973; Clark and Munro, 1975), as opposed to the forest. (See, for example, Reed (1988), who considered the optimal fishing policy in the case where the fish resource can randomly collapse.) A notable exception is the body of work centering around the Faustmann rotation model (Faustmann, 1849; Samuelson, 1976; Conrad, 1999). Natural hazards where first introduced in the Faustmann context to derive the optimal harvesting strategy in the case of fire occurrence (Routledge, 1980;

Reed, 1984), but we know of no study that does so in the context of endogenous prices.

Third, in theoretical forest economics, the long-term stability of forest stocks in the face of natural hazards with endogenous prices has yet to be investigated. Forest economics literature most often considers timber prices as constant in time (Reed, 1984). Even when assuming stochastic prices, prices are often independent from natural hazards (Yin and Newman, 1996; Loisel, 2011). One approach to capturing the price effects of natural disturbances - such as increased market supply, diminished quality of damaged timber, and higher costs of harvest due to increased demand - assumes that the price of timber diminishes by a given percentage following a crisis (Dieter, 2001), independent from the intensity of the natural hazard. In contrast, Knoke et al. (2021) separated cases of "local disturbance" and "extreme events", where damages are higher in the latter case. Another strategy is to consider price variations as random and independent from natural hazards. For example, Brazee and Mendelsohn (1988) suggested that wood prices followed independent and identically distributed processes, which can be Brownian (Yin and Newman, 1996; Knoke and Wurm, 2006) or normally distributed (Roessiger et al., 2013). Rakotoarison and Loisel (2017) assumed that timber price diminished several years after a storm. This approach enabled them to derive expected losses within a Faustmann framework. Their model is based on the stand scale (i.e. few hectares), which is much smaller than that at which timber prices are defined. We suggest to study the price volatility at a regional scale, where both price and timber quantity should be better defined. It must be noted that Rakotoarison and Loisel (2017) estimated the effect of price drop on the land expected value, making the assumption that the damages on a given stand are a good proxy for the local timber price variation. Like Rakotoarison and Loisel (2017), we consider two interdependent risks (Bastit et al., 2023): price risk and a long-term timber production risk which follows from it. This means that the price risk and the production are directly linked in our model.

We create a macro-stylised model that describes an equilibrium between forest inventory and growth and a timber market in the face of natural hazards. Specifically, we connect a forest model, which describes the biological growth of a forest inventory over time, to a market model, which describes the management (in our case, harvest) of the forest by forest owners. We nest an equilibrium-displacement model into the forest growth model to analyze the market response to natural disturbances (Kinnucan, 2016). Equilibrium-displacement models have often been used to explain short-term variations of timber markets to natural disturbances (Kinnucan, 2016; Sun, 2020), such as the drop in timber prices following hurricane Hugo in Florida in 1989. However, as suggested by Prestemon and Holmes (2000), they can be also used for long-term predictions. This enables to derive the critical inventory necessary to ensure the long-term existence of the forest inventory and the stability of the inventory in the face of stochastic natural disturbances.

We study the resilience of a social-ecological system in the sense that we consider a model with societal (timber market) and ecological (forest) subsystems (Renaud et al., 2010), the interactions of which lead to dynamics that would be unexpected without those interactions (Costanza et al., 1993). Measurements of resilience and stability have been particularly developed in ecology (Holling, 1973; Pimm, 1984; Gunderson and Holling, 2002; Arnoldi et al., 2016; Donohue et al., 2013). These include Holling's resilience of multiple equilibria (the maximum size of perturbation that a system can absorb and still return to its original state) (Holling, 1973), persistence (the time spent in a given equilibria) (Perrings, 1998), return time (time elapsed between two occurrences of a given natural hazard, corresponding to the inverse of the frequency of natural hazards) (Holmes et al., 2008) and variability (quantifies how far a parameter evolves from its mean) (Carpenter and Brock, 2006).

These methods have found their way into a large body of work measuring the resilience of coupled social-ecological systems (Perrings, 1998). For example, Reed (1988) derived the optimal management strategy for a fishery that can disappear due to a random natural catastrophic collapse. Anderies et al. (2002) developed a model to assess the resilience of grasslands subject to pressures of grazing and wildfires. Perrings and Walker (2004) suggested that the optimal use of rangeland is in fact not constant through time and should dynamically evolve. Kinzig et al. (2006) even went further by suggesting that resilience should not be defined by the evolution of a single parameter but by the co-evolution of several systems, acting at different scales, interacting with each other, creating highly nonlinear regimes. The contribution of Knoke et al. (2022) to assess the resilience of a temperate forest stand facing natural hazards is, to our knowledge, the only publication dealing with forest resilience in the forest economics literature. They estimated the time needed for a forest stand to return to its original value following a natural hazard, e.g. return time (Pimm, 1984). They evaluated different forest management strategies such as clear-cuts and harvesting to preserve continuous forest cover, focusing on the stand scale with constant prices. In contrast, we indirectly compute Holling's stability of multiple equilibria by measuring how the traits of the coupled forest-market can move the system from a state of long-term existence of the forest inventory to collapse. We then measure the return time of the system to equilibrium following a natural hazard.

In the contrast to the classical resource economics literature (Conrad and Clark, 1987; Conrad, 1999), we do not pursue an optimal policy, maximizing the profit of an individual forest owner or maximizing the welfare of society. We suggest a harvest policy in which harvest is elastic to price and the available volume of timber in the forest, which corresponds to an equilibrium that balances supply of timber by forest owners and timber demand by buyers. We assume a single decision maker who manages the entire forest inventory at a regional scale, with harvest levels adjusting to the stock of forest and market price of timber (both of which can change over time). We further assume that the market is not regulated by a policy maker and that the timber market smoothly responds to fluctuations in the forest stock and the harvest regime. The aim of our model is not to find optimal forest management policies, but to describe the conditions for the stability of our bio-economic equilibrium in the face of natural hazards.

The rest of our paper is organized as follows. Section 2 describes the theoretical model in two essential parts: forest inventory growth and the timber market. Section 3 presents the main results in the case of a small natural disturbance, and conditions to maintain the existence of a meta-stable equilibrium. The long-term dynamic of the timber market is then investigated. Section 4 is devoted to a discussion of the results. Finally, a brief conclusion and perspective is provided in Section 5.

2 Methods

2.1 The model

Fig. 1 summarises the different blocks of our model, illustrating the feedbacks between natural forest growth, forest management, the timber market model, and natural disturbances.

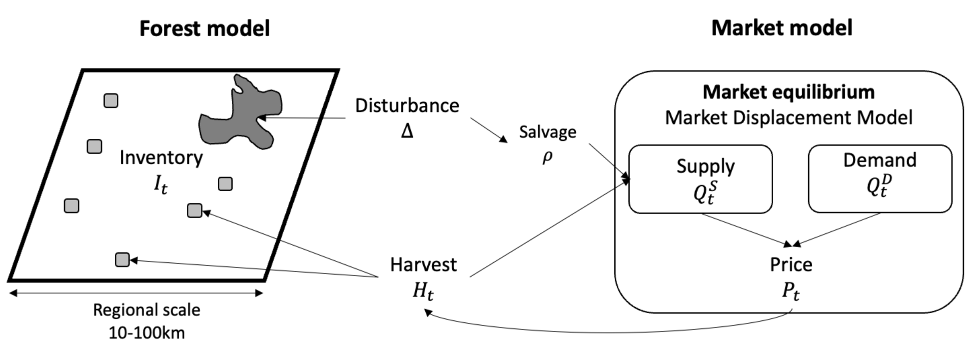

Figure 1: Graphical representation of the theoretical model.

The forest model We consider a forest inventory consisting of multiple stands (Fig. 1, left), representing the aggregate standing volume of timber available in a region independent from any age or diameter class[1]. We use a basic logistic function to describe the evolution of the forest standing timber in the absence of forest management and natural disturbance (Berryman et al., 1984), such that

$$I_{t+1} - I_t = g(I_t) = \frac{I_t}{\tau} \cdot \left(1 - \frac{I_t}{K_I}\right) \tag{1}$$

where τ corresponds to a characteristic time scale for the forest inventory evolution. It corresponds to the inverse of the traditional growth rate typical to logistic growth models. Forest growth is proportional to the

[1]It is possible to specify age classes and fix the evolution of each class separately (*sensu* Kuusela and Lintunen (2020)). However, this introduces more complexity to the model and is not central piece of this article.

inverse of τ. The greater its value, the slower the rate of timber growth. While our use of τ is contrary to a normal growth rate, as we will show below, this formulation will prove especially relevant when describing the return time to equilibrium following a disturbance. The parameter K_I represents the maximum carrying capacity of the forest, or the maximum amount of available timber in the region if there were neither harvest nor natural hazard. We further generalize Eq. (1) such that K_I, and by extension I_t, is normalized to 1 and $0 < I_t < 1$.

This shape of the logistic function implies that if there is neither harvest nor natural disturbance, the size of the forest inventory is increasing as long as $I_t < K_I$. As we normalize Eq. (1), growth reaches a maximum when $I_t = 0.5$, i.e. when the inventory is at half its maximum. Moreover, the shape of the curve is symmetrical with respect to 0.5. Albeit using a logistic function is less precise than yield tables, it captures well the phases of forest inventory growth: a slow initial phase (young forest), fast growth at intermediate volumes, and then decreasing growth until inventory reaches its carrying capacity (Berryman et al., 1984).

Forest management The forest inventory is managed by a single decision-maker who decides in each period to harvest a quantity H_t of the inventory I_t, which is sold on the timber market at price P_t. The quantity of timber harvested at a period t depends on the timber price P_t and the total inventory I_t such that,

$$H_t = h \cdot P_t^{\varepsilon_{PH}} \cdot I_t^{\varepsilon_{IH}} \tag{2}$$

where h is a constant describing the harvest intensity, and ε_{PH} and ε_{IH} are constant elasticities of harvest with respect to price and inventory respectively (Sun, 2020). The last two represent the percent change in harvest for changes in price or inventory size (e.g., if price increases by 1%, then harvest will increase by ε_{PH}%). We would expect $\varepsilon_{PH} > 0$, as harvest should increase with price (Kinnucan, 2016). Similarly, we would also expect $\varepsilon_{IH} > 0$, as harvest should scale with forest inventory size (Prestemon and Holmes, 2004). The multiplicative shape of H_t is commonly used in equilibrium-displacement models (Prestemon and Holmes, 2004; Kinnucan, 2016; Sun, 2020). For instance, this is this non zero harvest elasticity to price that enables to consider endogenous timber price.

Natural disturbance To quantify the effect of natural disturbance, we introduce a generic natural hazard and quantify its effects as a share Δ of the forest that is affected. It corresponds to the damage of a single event such as a fire or a windstorm, but - as damage is expressed in terms of generic volume loss (Reed, 1984) - it can depict more generally all the possible damages that can impact timber stocks in a forest. Multiple natural hazards could also be considered in the single distribution of damage.

Market equilibrium The supply of timber to the market consists of harvested timber and the quantity of salvageable timber brought to the market by a natural disturbance,

$$Q_t^S = \begin{cases} H_t + \rho \cdot \Delta \cdot I_t & \text{if a hazard occurs} \\ H_t & \text{otherwise} \end{cases} \tag{3}$$

where, when a natural disturbance occurs, a fraction ρ of the fallen timber is salvaged and sold on the market[2]. We assume that all harvested timber is sent to the market, i.e. there is no self-consumption, timber black market, or timber production via natural mortality.

Market demand for timber depends only on price such that:

$$Q_t^D = q \cdot P_t^{\varepsilon_{PD}} \tag{4}$$

where ε_{PD} is a constant elasticity of demand to price, and q is a constant. As per the classic supply and demand curves, we expect ε_{PD} to be negative. Moreover, we suppose that the market reaches an equilibrium between supply and demand at each moment in time, or more formally,

[2] Several effects lead to ρ being less than 1 (imperfect efficiency). We would expect a fraction of fallen timber to be too damaged to be sold on the market. Furthermore, as greater amounts of stock are downed, forest owners are not able to properly salvage it and it may become unusable. Thus we would expect ρ to decrease with the intensity of damages.

$$Q_t^D(P_t) = Q_t^S(P_t, I_t) \tag{5}$$

That is, in each period, supply Q_t^S and demand Q_t^D instantaneously adjust to their market equilibrium price P_t and quantity, the latter of which is determined by harvest and natural disturbance (if it occurs). There are no delays between the forest being harvested (or damaged), brought to the market, and then the market adjusting to the new supply.

The full coupled social-ecological system The dynamics of the full social-ecological system can be written as,

$$I_{t+1} - I_t = \begin{cases} g(I_t) - H_t - \Delta \cdot I_t & \text{if a hazard occurs} \\ g(I_t) - H_t & \text{otherwise} \end{cases} \tag{6}$$

$$H_t = h \cdot P_t^{\varepsilon_{PH}} \cdot I_t^{\varepsilon_{IH}} \tag{7}$$

$$P_t = \begin{cases} \left[\frac{H_t}{q} + \frac{\rho}{q} \cdot \Delta \cdot I_t\right]^{\frac{1}{\varepsilon_{PD}}} & \text{if a hazard occurs} \\ \left[\frac{H_t}{q}\right]^{\frac{1}{\varepsilon_{PD}}} & \text{otherwise} \end{cases} \tag{8}$$

which is a system of three equations and three unknowns and, given an initial level of forest inventory, can be solved for values of I_t, H_t, and P_t over time.

In the absence of disturbance, the long-term steady-state is reached when the natural growth (left side of Eq. (9), see Fig. 2 black line) equals the quantity that is harvested (left side of Eq. (9). To estimate this, we re-inject the price in case of no hazard (Eq. (8)) into Eq. (4). All in all, long-term steady forest inventory (I^*) verifies of the following equation:

$$\frac{I^*}{\tau} \cdot (1 - \frac{I^*}{K_I}) = q\left(\frac{h}{q} \cdot (I^*)^{\varepsilon_{IH}}\right)^{\frac{\varepsilon_{PD}}{\varepsilon_{PD} - \varepsilon_{PH}}} \tag{9}$$

which can have one, two, or three possible steady-state values, depending on parameter values of τ, h, q and different elasticities (Fig. 2). I^* corresponds to the largest solution of the set of possible solutions. Equilibrium values for harvest (H^*) and price (P^*) can be solved using the equilibrium forest inventory in Eq. (9) and equations (7) and (8).

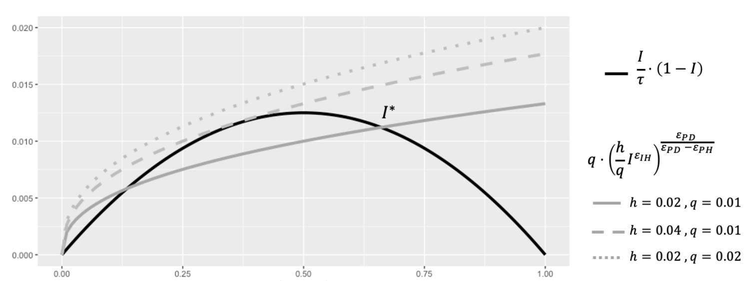

Figure 2: Graphic summing up the equilibrium states for different parameterizations. The black line corresponds to the left side of Eq. (9), whereas the grey lines correspond to the right side of Eq. (9) for different values of h and q. The solid line has three solutions, the long-dashed line has only two solutions, and the dashed line only accepts the trivial solution.

Model analysis We analyze the model by first determining the short and long-term effects of a single disturbance. We then focus on the recovery of the system following a natural disturbance and the long-term survival of the forest inventory in the face of multiple disturbances. For the former, we treat the initial state of the forest as free and evaluate the relationship between the magnitude of the disturbance and the critical inventory necessary to prevent inventory collapse. For the latter, we set the initial state of the system at equilibrium, measure the time it takes for the system to return to its previous level following a disturbance, and determine the return time between disturbances needed to prevent collapse. We derive analytical results when possible, but as the system of equations in (6)-(8) has no closed-form solution, we rely on numerical simulations when analytical results are not feasible. Parameter values for numerical simulations were calibrated from the forest literature. Baseline values can be found in Table 1.

Symbol	Description	Value [Variation range]
ε_{IH}	Elasticity of harvest to inventory	1^a [0.2 ; 1.46]
ε_{PH}	Elasticity of harvest to price	0.5^b [0.25 ; 0.55]
ε_{PD}	Elasticity of demand to price	-0.35^b [-0.43 ; -0.57]
ε	Elasticity of harvest to damages (Eq. (11))	0.41 [0.35 ; 0.83]
ρ	Salvageable share	0.3
τ	Time of evolution of our system	55
K_I	Maximum carrying capacity	1
h	Harvest intensity	0.01
q	Level of demand for timber products	0.02

Table 1: Baseline values for the main parameters used in the study. Approximated from: [a]Binkley (1993), [b]Newman (1987).

3 Results

3.1 General effects of a single disturbance

We will first look at the effects of a single disturbance (Δ) on the social-ecological system at time t_Δ. We can separate the effects of a natural disturbance into two categories: a short-term price drop effect due to an influx of timber supplied to the market, and a long-term existence effect of the forest inventory (Prestemon and Holmes, 2000).

In the short term, the quantity of timber on the market is larger than that with no disturbance. Foresters must sell their salvageable timber, which, in accordance with the supply curve in Eq. (3), leads to excess supply in the market and a drop in price. In other words, when foresters sell their timber following a disturbance, they do so at a lower price than they would with no disturbance.

It is important to note that this drop in price is strongly correlated with the proportion of fallen timber that can be salvaged and sold on the market (ρ), the scalar (q), and the elasticity of the demand function (ε_{PD}). In particular, as foresters lose efficiency in salvaging fallen timber or natural hazards are more damaging, there is less excess timber supplied to the market and the short-term effects of the hazard are felt less in changes in price and more by changes in the forest inventory. Indeed, by taking the partial derivative of Eq. (2) with respect to the forest inventory (I_t), it is straightforward to show that a decline in inventory size leads to a decrease in harvest rates (all else held equal).

In addition to the short-term effects, which only last through the salvage period (a few quarters), disturbances can affect the long-term existence of the forest inventory (Fig. 3). Define $I_{t_\Delta^+}$ as the level of forest inventory following a disturbance. Several trajectories, beginning from $I_{t_\Delta^+}$, are possible. The inventory can either follow a track going toward its previous target value I^*, but a long-term exhaustion of the inventory can also be undertaken.

From Eq. (1), in the absence of harvest or disturbance, the forest inventory would always tend to its long-term carrying capacity (K) as long as $I_t > 0$ (Gotelli, 1995). Therefore, the existence or collapse of the forest inventory depends on the market effects following a natural hazard.

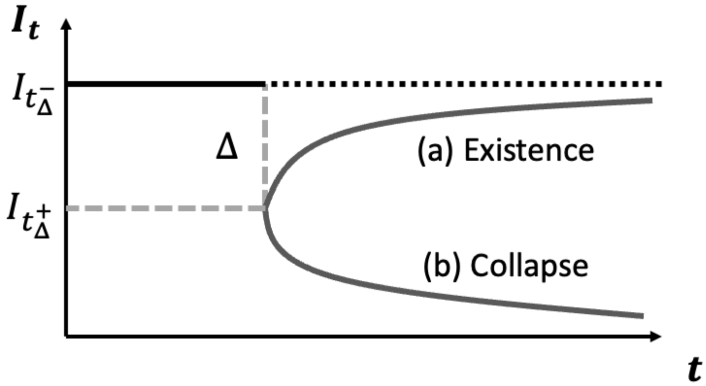

Figure 3: Criterion to define stability: if the inventory goes back up (resp. goes to 0) after a disturbance Δ, the equilibrium is Δ-stable (resp. Δ-unstable) as in case (a) (resp. case (b)).

The market effect In the absence of natural disturbance, the market price and harvest rates are tied directly to the level of the forest inventory. Disturbances, through the market effect, decouple this one-to-one linkage and can lead to the over-exploitation of the forest inventory to depletion.

Let us suppose that a disturbance occurs at time t_Δ. We call t_Δ^-, the time just before the hazard, i.e. not yet affected by the hazard, and t_Δ^+, the time just after the disturbance where the short-term effects (such as the short-term price drop) are not playing a major role anymore: the market is back on its long-term trajectory. The new price $P_{t_\Delta^+}$ is defined by the market equilibrium between demand $Q^D(P_{t_\Delta^+})$ and supply $Q^S(P_{t_\Delta^+}, I_{t_\Delta^+})$, where[3]

$$P_{t_\Delta^+} = \left(\frac{h}{q} \cdot I_{t_\Delta^-} \cdot (1-\Delta)\right)^{\frac{\varepsilon_{IH}}{\varepsilon_{PD}-\varepsilon_{PH}}} = P_{t_\Delta^-} \cdot (1-\Delta)^{\frac{\varepsilon_{IH}}{\varepsilon_{PD}-\varepsilon_{PH}}} > P_{t_\Delta^-} \tag{10}$$

After the initial short-term price drop to the influx of timber to the market (see above), timber prices rise over time as expected due to scarcity in the resource ($\frac{\varepsilon_{IH}}{\varepsilon_{PD}-\varepsilon_{PH}} < 0$). The new price being known, it follows from Eq. (7) that harvest can be expressed as,

$$H_{t_\Delta^+} = H_{t_\Delta^-} \cdot (1-\Delta)^{\varepsilon} < H_{t_\Delta^-} \quad \text{where} \quad \varepsilon = \frac{\varepsilon_{IH} \cdot \varepsilon_{PD}}{\varepsilon_{PD} - \varepsilon_{PH}} = \frac{\varepsilon_{IH}}{1 + |\frac{\varepsilon_{PH}}{\varepsilon_{PD}}|} \tag{11}$$

where ε can be interpreted as the harvest elasticity to disturbance. In other words, if the inventory is diminished by 1%, i.e. $\Delta = 0.01$, harvest is reduced by ε%. The elegance of this aggregated parameter is that it summarizes the three elasticities into a single parameter that takes into account the long-term effect of natural hazard on harvest.

If a disturbance is sufficiently large, the market decouples from the forest inventory and the forest is not able to biologically produce what is demanded from the timber market. Harvest exceeds forest growth, a trend which, because of constant elasticities of harvest, price, and demand, continues until the depletion of the forest inventory. Reductions in harvest in response to lower inventories still exceed forest regeneration. It is clear that the parameter Δ, the level of damage from a natural hazard, is the key parameter of our study. In the following section, we investigate the level of Δ required to destabilize the timber market equilibrium and lead to the collapse of the forest inventory.

3.2 The minimal inventory of equilibrium

In this section, we study the size of a single disturbance necessary to induce the collapse of the forest inventory. As the system of equations in (6)-(8) has no closed-form solution and depends on parameter values (see Eq. (9) and Fig. 2), analytical results are difficult to obtain and we rely on numerical simulations. However, if

[3]To see this, note that $I_{t_\Delta^+} = (1-\Delta) \cdot I_{t_\Delta^-}$, substitute it into Eqs. (7) and (8), and solve for $P_{t_\Delta^+}$.

we assume that the disturbance is small, we can obtain analytical results by focusing on the dynamics of the system around its equilibrium.

Supposing that Δ is small, it is possible to linearize the system by taking a first-order Taylor approximation in Δ to study the response of the system to disturbance in the vicinity of its equilibrium I^*. This manipulation is equivalent to calculating the eigenvalue of the problem near its equilibrium (Clark, 2010). Doing so allows us to derive an inequality that holds if the forest inventory moves towards collapse,

$$\frac{I^*}{\tau} \cdot (1-\Delta) \cdot (1 - I^* \cdot (1-\Delta)) < q \cdot \left(\left(\frac{h}{q} \right)^{\frac{1}{\varepsilon_{IH}}} \cdot I^* \right)^{\varepsilon} \cdot (1 - \varepsilon \cdot \Delta) \tag{12}$$

where the inequality (12) is first-order in I^*. Re-arranging allows us to define a critical threshold $\mathcal{I}^*_\varepsilon$ under which there cannot exist any inventory of equilibrium $I^* > 0$.

$$I^* < \mathcal{I}^*_\varepsilon = \frac{1-\varepsilon}{2-\varepsilon} \tag{13}$$

Even though the disturbance is "small", it is possible for the disturbance to move the system from a state of persistence to that of collapse. There exists a nonlinear relationship between the size of the natural disturbance necessary to collapse the forest inventory and the elasticity of harvest to disturbance, which is due to the nonlinear growth of the forest inventory (Fig. 2). In general we would expect $I^*_\varepsilon > 0.5$, which is where the growth of the forest inventory is at its maximum. Indeed, regardless of changes in price and adjustments in harvest, harvest must outpace forest growth in order for the inventory to go to collapse - which is less likely if the inventory stock is at its inflection point. We plot the relationship between $\mathcal{I}^*_\varepsilon$ and ε in Fig. 4. Calibrating the individual elasticities of ε from the literature (see Eq. (11) and Table 1) suggests that range of ε varies between 0.35 and 0.83. Within this range of ε, I^*_ε varies between 0.4 and 0.15.

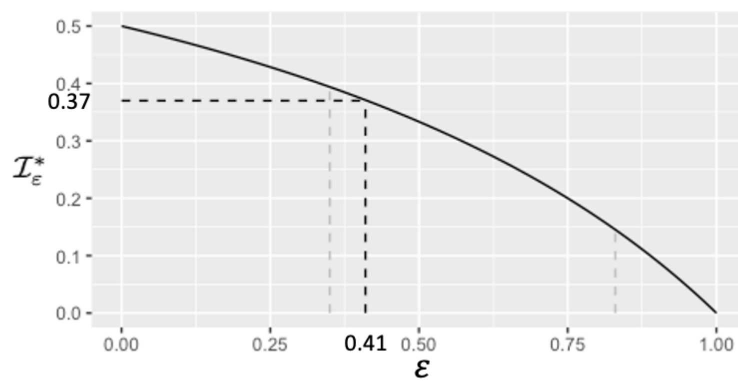

Figure 4: Critical inventory $\mathcal{I}^*_\varepsilon$ with respect to ε. The literature suggests $\varepsilon \sim 0.41$ (black dotted line), giving $\mathcal{I}^*_{\varepsilon=0.41} = 0.37$. Grey dotted lines represent the expected range of values of ε from the literature. Values of $\varepsilon < 0$ or $\varepsilon > 1$ lead to either inventory collapse (former) or infeasible levels of the inventory (latter, $\mathcal{I}^*_\varepsilon > 1$.)

We extend our results via numerical simulations in Fig. 5, which depicts the long-term persistence of the forest inventory for all levels of disturbances (not only small ones). For all $I^* \leq \mathcal{I}^*_\varepsilon$, the forest collapses, regardless of the initial inventory before the disturbance. An interesting corollary is that if $I^* > \mathcal{I}^*_\varepsilon$, then there exists some level of disturbance that the market can support and come back to its equilibrium. We will now concentrate on the case where $I^* > \mathcal{I}^*_\varepsilon$ and find thresholds over Δ and $I^+_{t_\Delta}$ that ensure the sustainability of the forest inventory.

3.3 Critical inventory for collapse

To do so, we generalize our results for all possible values of Δ to determine the minimum level of inventory I^Δ, ensuring that if $I_t > I^{\Delta^*}$, the dynamic of the system remains in the existence domain. This problem is strictly equivalent to looking for the level of disturbance $\Delta^*_{I^*}$ required to destabilize the system at equilibrium

I^* and lead to the collapse of the forest inventory. In another words, I^{Δ^*} corresponds to the minimum level of inventory required to stay on the existence path and $\Delta^*_{I^*}$ is the maximum disturbance that the inventory can cope with. The link between both variables is given by $I^{\Delta^*} = (1 - \Delta^*_{I^*}) \cdot I^*$.

$\Delta^*_{I^*}$ is indeed the solution of Eq. (14). This equation cannot be analytically solved, so we rely on numerics for its solution. Fig. 5A exhibits the solutions of the problem in terms of $\Delta^*_{I^*}$, whereas Fig. 5B focuses on the response in the forest inventory.

$$\frac{1 - I^* \,.\, (1 - \Delta^*_{I^*})}{1 - I^*} = (1 - \Delta^*_{I^*})^{\varepsilon - 1} \tag{14}$$

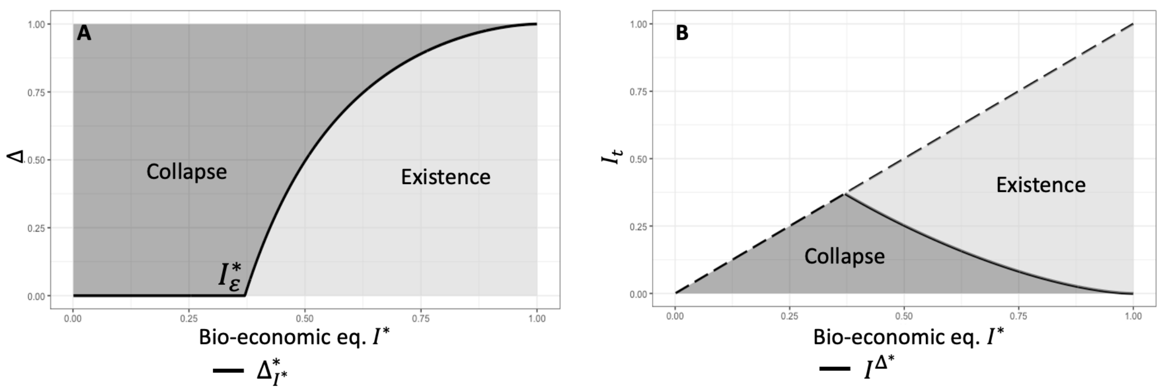

Figure 5: Stability of the equilibrium for every possible bio-economic equilibrium I^* depending on the level of damage Δ (left) and inventory after disturbance (right). The grey part is stable (inventory goes back to equilibrium I^*) whereas the red one is unstable (inventory is depleted).

To conclude, even if the inventory of equilibrium I^* is larger than $\mathcal{I}^*_\varepsilon$, if a disturbance of severity $\Delta > \Delta^*_{I^*}$ occurs, it still leads to a dynamic of inventory depletion. For the interested reader, Appendix A extends Fig. 3 (left) to every possible ε values.

3.4 Minimum return time from natural hazard

In the previous section, we considered how large a single disturbance must be to destabilize the forest inventory and lead to its collapse. Now we focus on another perspective of the problem: the relevant time scale for the forest inventory to recover following a disturbance. To do so, it is useful to have a reference point by which to compare numerical simulations. Therefore, we start each simulation at equilibrium using our baseline parameter values, apply a disturbance, and measure the time it takes for the system to return to its equilibrium or collapse.

Unfortunately, the differential equation describing I_t has no closed-form analytical solution. However, as suggested on Fig. 6 (left) we can define a time θ, as a function of I^* and Δ, that characterizes the time scale needed to come back to equilibrium. If the inventory grows at a rate $g(I_{t^+_\Delta}) - H_{t^+_\Delta}$ following a disturbance Δ, then the link between θ, I^* and Δ can be written as,

$$\theta = \frac{\Delta \cdot I^*}{\frac{dI}{dt}} \tag{15}$$

where θ approximates the minimum mean return time of the natural hazard to its former equilibrium, assuming that multiple disturbances follow each other and have the same intensity. If disturbances are spaced further apart in time than θ, the inventory will persist. Fig. 6 shows how θ varies for the different combinations of I^* and Δ. For example, in the case where the equilibrium forest inventory is $I^* = 0.75$ and the disturbance has a strength $\Delta = 20\%$, the maximum return time of the disturbance is $\theta = 2.2\,\tau$ (see the white cross on Fig. 6, right). In our baseline parameter values, τ would be around 50 years. This means that a major disturbance should not occur more than every 110 years.

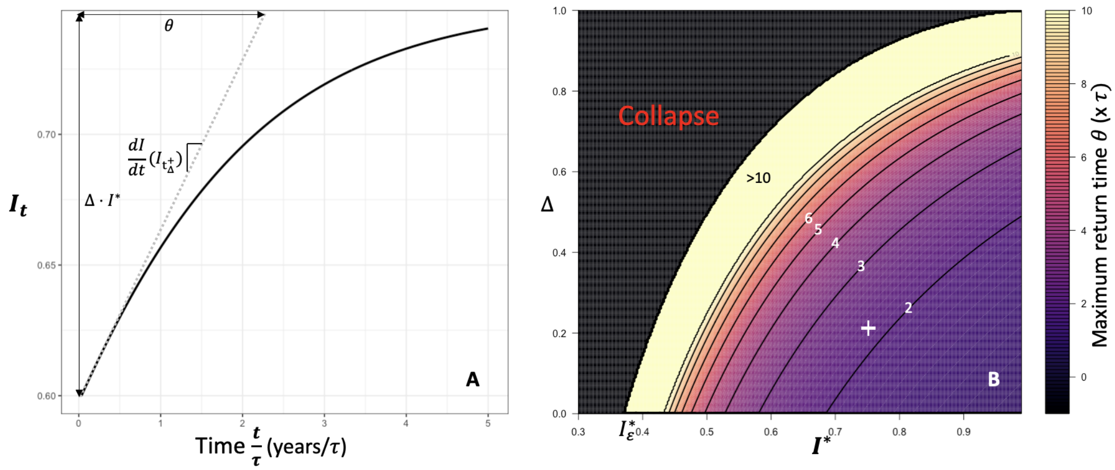

Figure 6: *Left*: Evolution of the forest inventory I_t in the case of $I^* = 0.75$, $\Delta = 0.2$. *Right*: Graphic of the normalized maximum return time of disturbance $\frac{\theta}{\tau}$ for the different values of I^* and Δ. Note that the white cross corresponds to the left example.

In addition, Fig. 6 shows that for small inventories (lower than 0.5), whatever the disturbance, the time between two disturbances should be at least 5τ (i.e. more than 250 years). This result moderates the fact that the market helps to stabilise the forest inventory. Even if this can help the stabilization, it also strongly slows down the dynamic of the system such that the frequency of disturbances should stay low. This result also suggests that the effects of a disturbance on both timber market and forest inventory can linger for a very long time (several decades).

3.5 Persistence of the forest inventory in the face of multiple natural disturbances

The previous sections gave us intuition regarding the effects of a single disturbance (happening regularly with the same level of damages) on the forest inventory and the relevant timescale of its recovery. However, at the timescale of the life of a forest inventory, natural disturbances are likely to come in spades. Here we assign a distribution to Δ and evaluate the time spent at its long-term persistent equilibrium I^* as a function of the mean and standard deviation of the distribution of Δ.

Suppose that the yearly damages from natural disturbances $\Delta_{p,d}$ is a random variable, following a Bernoulli distribution with the parameters p (probability of occurrence) and d (magnitude of damages),

$$\Delta_{p,d} = \begin{cases} d & \text{with probability } p \\ 0 & \text{with probability } 1-p \end{cases} \tag{16}$$

which has a mean and standard deviation of $p \cdot d$ and $(1-p) \cdot p \cdot d^2$ respectively. We assume that the distribution of $\Delta_{p,d}$ does not vary over time. The advantage of a Bernoulli are threefold: first, it is simple and intuitive; second, it lines up well with traditional definitions of risk (Knight, 1921); third, by fine-tuning the parameters p and d, it can be calibrated to a diversity of natural hazards which can vary in frequency and/or damages.

As before, we set the parameters at their baseline values, initialize the model at equilibrium, and measure the average time the forest inventory spends at its long-term equilibrium value. Using Monte Carlo simulations, we estimate the average time t that is needed to move from the I^* equilibrium to the minimum level of inventory ensuring existence ($I_t < I^{\Delta^*}$). t can be seen as a mean survival time, because it corresponds to the mean time during which the inventory stays on the existence track. We ran 500 simulations for each combination of mean and standard deviations 500 simulations with a temporal horizon of 1000 years.

Fig. 7 shows that mean survival time is reduced when the mean of the damage is increasing but also when the standard deviation is increasing. It is quite straightforward to understand why the time elapsed before changing the equilibrium is negatively correlated with the mean damages: the more damage there are, the more quickly the minimal threshold of inventory is reached. However, the effect of standard deviation is a bit more complicated: when standard deviation increases, the mean being fixed, this time is also diminished. This means that rare and large natural hazards are more harmful to the long-term resilience of the equilibrium than small and regular events. Note that this effect disappears above the orange line, because this would correspond to events with damages larger than 100%, which is not possible.[4]

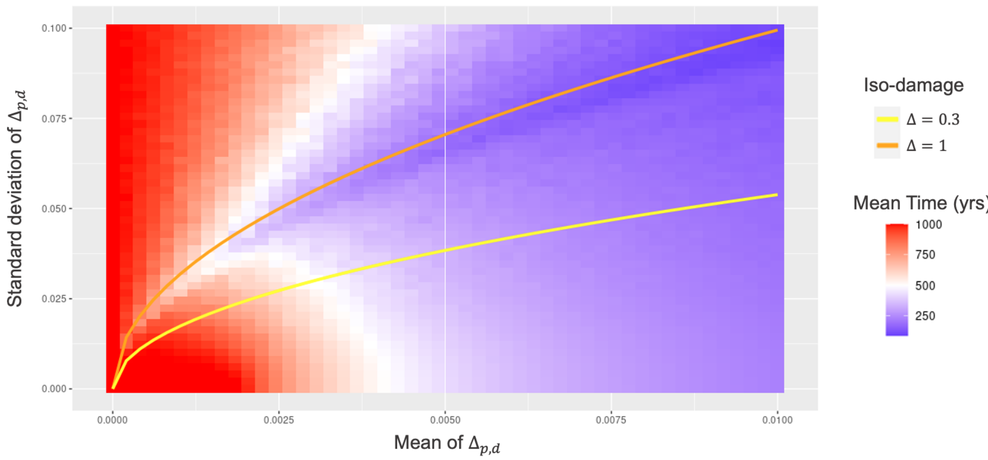

Figure 7: Heatmap showing the mean time spent needed to go from equilibrium I^* to a level where the market is collapsing. All points above the orange curve cannot be reached because they represent damages larger than 100% of the stand. The yellow curve represents constant 30% expected damages. (Parameters: $I^* = 0.75$, and $\tau = 55$ years, maximum time limit is set to 1000 years).

4 Discussion

One of our key findings is that natural disturbances can break the linkage between harvest and the forest inventory, leading to the over-exploitation of the forest stock and its eventual depletion. This resonates well with the classic findings in resource economics of the Tragedy of the Commons (Hardin, 1968), Easter Island (Brander and Taylor, 1998; Good and Reuveny, 2006), and the exploitation of fisheries (Clark, 1973). In these cases, even with forward-looking behavior, in the case of absence of property rights, limited foresight or high discount rate, it is possible to over-exploit the resource and drive it to depletion.

In our case, the destabilization of the forest inventory comes as a result of the market effect (as opposed to forest growth - in the absence of harvest, a logistic growth function will always return to its carrying capacity if the inventory is greater than zero). Assuming effective monitory of the forest inventory following a disturbance or disturbances, a public policy could be implemented if the inventory falls below the critical threshold I^*_ε to prevent the over-exploitation of the resource. Harvest is determined by price (Eq. (8)). Therefore, we could imagine an intervention such as a timber tax to reduce demand and subsequently deforestation. Alternatively, we could envision policies designed to increase the resilience of the inventory to natural disturbances, such as subsidies for plantations (aid in the recovery following a disturbance) or adaptive strategies (decrease the magnitude of damages). For example, the EU Commission has framed some conditions under which a member state can "aid to prevent and repair damage to forests caused by forest fires, natural disasters, adverse climatic events which can be assimilated to natural disasters, other adverse climatic events, plant pests and catastrophic events" (European Union (EU), 2014). This enables the European member states to subsidy several actions reducing the risk of wildfires, for example.

Both the frequency and intensity of natural disturbances are expected to increase in the future as a result of climate change (IPCC, 2012; Machado Nunes Romeiro et al., 2022). Furthermore, the interactions

[4]The reason for this effect is that the substitution of probability to get larger damages is useless when damages are larger than one.

between different types of natural hazards (e.g., storms, fires, and pest outbreaks) is expected to increase as well (Buma, 2015; Seidl et al., 2017; Ridder et al., 2022), leading to multi-risk situations and cascade effects that stress the forest inventory. In the same way, Buma (2015) claims that natural hazard can interact with each other and lead to cascades of hazards, concentrated around few main events. Ridder et al. (2022) demonstrated that the occurrence of compound events should increase in the the future due to climate change. We could use our model to assess some impacts of climate change on timber market. Additionally, climate change is linked to increased timber demand (Cowie et al., 2021). Biomass sourced products, such as fuel wood (Favero et al., 2020), produce less carbon dioxide than their fossil fuel counterparts, making them potential favourable options in the future. On the demand side, this would decrease ε_{PD} and subsequently decrease ε, leading to an overall increase in $\mathcal{I}^*_\varepsilon$. In other words, we would require a higher level of forest inventory to prevent its long-term collapse.

Interestingly, in our model with endogenous prices, the forest inventory is more resistant to collapse than inventories in similar models with constant prices. With constant prices, demand and supply are constant, so that a sustainable trajectory requires $I_t > 0.5$. In our model, endogenous prices decrease demand when the resource becomes more scarce. Harvest being reduced is a stabilizing effect of the market and enables us to have an equilibrium I^* smaller than 0.5 (even if it should remain larger than $\mathcal{I}^*_\varepsilon$, which is smaller than 0.5).

While our framework is simple, we believe that it effectively captures the effective dynamic of the forest inventory, the market, and natural disturbances. Certainly incorporating greater complexity in the model could add a deeper touch of reality, but doing so quickly complicates the analysis. Even in our simple setting, general analytical results are not always feasible. Nonetheless, our approach is not without its limitations. We discuss several of these in turn.

Myopic harvest agents One of our strongest assumptions in the model is that agents are myopic and consider only the present in their management decisions. Implementing forward-looking behavior - not necessarily dynamic optimization, but discounting or a "sustainability" or preservation threshold - would likely stabilize the forest inventory and minimize the market effect following a natural hazard. Nor is our model optimal, either in a static (maximize benefits today) or dynamic sense (maximize benefits for a set time period). Indeed, in optimal control problems in resource economics, seldom is it optimal to completely exhaust the resource (Conrad and Clark, 1987; Clark, 2010). In forestry terms, as the resource becomes scarce, its "shadow value" or the value of an extra unit of forest increases and prevents its complete depletion.[5] We can partially account for this behavior by adjusting the elasticity of harvest to the forest inventory, ε_{IH}. Increasing ε_{IH} leads to a more cautious harvester that responds to declines in the inventory by more strongly reducing their harvest rates. It can be shown that increasing ε_{IH} lowers the critical inventory threshold $\mathcal{I}^*_\varepsilon$.

An autartic economy In this paper we consider a regional timber market that operates with perfect efficiency. Supply and demand are governed locally by the dynamics of the forest inventory without imports or exports of raw wood materials. However, the timber market is global. Implementing trade could affect the stability of the forest inventory. In the short term, we would expect our price drop in the regional market to cause a jump in exportation, as the global price would likely remain constant following a regional-scale disturbance. This has been discussed by Kinnucan (2016) and Sun (2020), especially on the relevant time scales to consider to modify the local trade habits. In the long term, we might expect trade to limit the increase in timber price following a disturbance - local demand could be satisfied by importation of timber - which would provide a strong stabilizing effect to the system.

Constant parameter values We treat our baseline parameter values as constant over time. Relaxing these assumptions could shift the value of our critical threshold $\mathcal{I}^*_\varepsilon$, return time, and resilience of the inventory in the face of multiple hazards. For instance, with rising temperatures and carbon dioxide concentrations, mean forest growth is expected to increase (Pretzsch et al., 2014) in the future, at least in the short term.

[5] A notable exception is Clark and Munro (1975), who illustrated that if the benefits of harvesting a fishery can be re-invested in natural capital, then it can be optimal to drive the stock to extinction. Similar behaviors can be observed when the value of the resource at the end of the management time horizon or scrap value is zero, or when a manager places zero value on future benefits (e.g., the discount rate approaches infinity) (Conrad and Clark, 1987).

This would reduce the value of τ, thereby increasing the growth rate and the ability of the forest inventory to recover following a disturbance. Similarly, the equilibrium-displacement model supposes constant market elasticities even when $\Delta > 20\%$, which is exceedingly large (Sun, 2020). We could also, for example, expect forest owners to change their harvesting behavior if the forest inventory is nearing collapse.

5 Conclusion

In this article, we suggest to assess the stability of a timber bio-economic equilibrium. To do so, an equilibrium between the timber produced by a forest and a timber market is disturbed by a natural hazard. Our key findings are that, with reasonable assumptions, there should always exist a minimal forest inventory to have a stable, equilibrium of the forest inventory. Over this minimal inventory, the equilibrium is always "meta-stable" and can always be lost if a large enough disturbance occurs. Such a severe disturbance is however unlikely, even if this could change in the future due to climate change.

We have assessed the stability of the market equilibrium but it would be very interesting to dig further in this model by calibrating it to specific types of disturbances or events and see the effective evolution of the forest inventory, timber price and quantities sold over time. For example, a model linking storm effects and bark beetle damage could be introduced in order to model explicitly an interaction between these hazards and understand the different processes at work when a major disturbance hits a forest at a large scale.

The model may also be used to analyze the coverage of both the production and price risks considered. For example, timber storage is a measure that is encouraged and funded by public authorities after extreme windstorms in order to prevent the price decreases. Such storage areas were implemented after windstorms Lothar and Martin in France and Germany in 1999. This public policy tool may be simulated in the model. In the same way, the model may serve to determine floor price under which the bio-economic equilibrium become unstable. Finally, insurance may be studied to cover production risk.

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A Sensitivity to ε

B Calculation details

By definition, at the equilibrium, the forest is growing at the speed it is harvested (with H^* the equilibrium harvest). This means that the equation of the equilibrium is:

$$\frac{I^*}{\tau} \cdot (1 - I^*) = H^*$$

Let's suppose that a disturbance Δ impacts this equilibrium. The new forest growth corresponds to:

$$\frac{I^* \cdot (1 - \Delta)}{\tau} \cdot (1 - I^* \cdot (1 - \Delta)) = g(I^* \cdot (1 - \Delta))$$

Whereas the harvest level is given by Eq. (11):

$$H = H^* \cdot (1 - \Delta)^{\varepsilon}$$

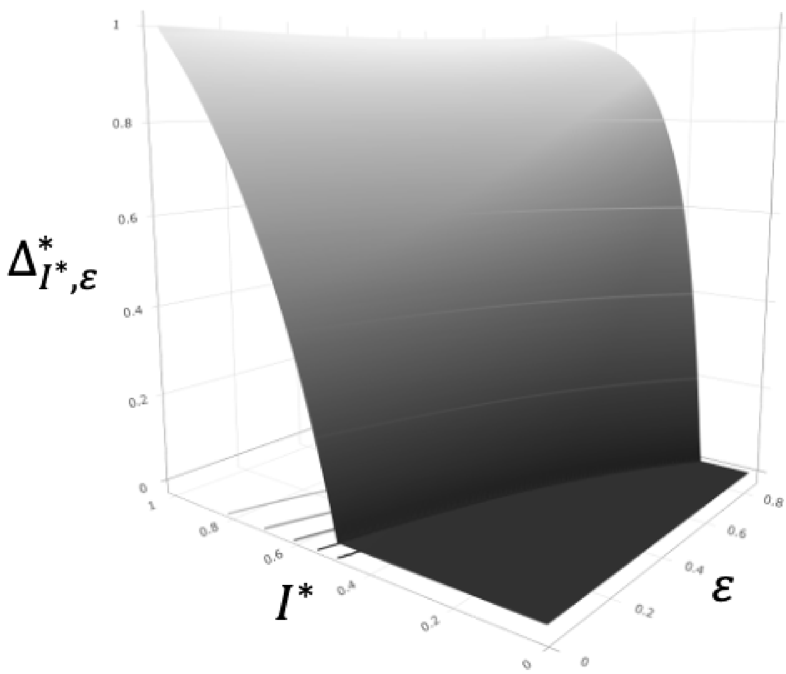

Figure 8: Maximum disturbance to stay in the I^* stable equilibrium for every possible bio-economic equilibrium I^* and every possible levels of elasticity ε.

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The inventory is on the existence path if the natural growth exceeds the harvest level, i.e. if:

$$\frac{I^* \cdot (1-\Delta)}{\tau} \cdot (1 - I^* \cdot (1-\Delta)) = H^* \cdot (1-\Delta)^{\varepsilon}$$

By replacing H^* we find Eq. (14). This equation has no analytical solution in the general case. We can however linearize it in the case where Δ is small with respect to 1. To do this, we make a Taylor expansion of $(1-\Delta)^{\varepsilon}$.

This leads to the following equation that can be re-injected in the previous one and thus leads to Eq. (13).

$$(1-\Delta)^{\varepsilon} \approx 1 - \varepsilon \cdot \Delta \quad \textbf{if} \quad \Delta << 1$$

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