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To cite this version:

Sylvain Caurla, Antonello Lobianco. Estimating climate service value in forestry : The case of climate information on drought for maritime pine in Southwestern France. Climate services, 2020, 17, pp.100106. 10.1016/j.cliser.2019.100106 . hal-02617889

HAL Id: hal-02617889
https://hal.inrae.fr/hal-02617889

Submitted on 13 Apr 2022

Climate Services 17 (2020) 100106

Contents lists available at ScienceDirect

Climate Services

journal homepage: www.elsevier.com/locate/cliser

Original research article

Estimating climate service value in forestry: The case of climate information on drought for maritime pine in Southwestern France

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ARTICLE INFO

Keywords:
Climate service value
Forest
Drought
Forest economics
Optimal harvesting age

ABSTRACT

In Western Europe, future climate changes go hand-in-hand with increasing risks of droughts and heat waves during summer. For forest ecosystems, a drought may result in both an increase in tree mortality and a reduction in tree growth. These impacts are delayed over time, i.e., there is a time gap between the drought and its impacts on the forest stand, which makes it possible to adjust forest management practices and, in particular, to prematurely harvest the impacted stand and to replant a new one if it is economically profitable to do so. Consequently, we define Climate Services (CS) as the information that supports forest owners in their decision to prematurely harvest or not after a drought. Our paper aims at developing a method to estimate the economic value of these CS in the case of a maritime pine stand in Southwestern France. Using a comparison of Land Expected Values (LEV) over an infinite period of forest rotations, our analysis suggests that the Climate Service Value (CSV) is highly dependent on three characteristics: (1) the age of the forest exposed to the drought; (2) the intensity of the drought in terms of both mortality and growth impacts; and (3) the discount rate value used. Overall, for a 2% discount rate for a young stand (less than 15–20 years old), the CSV is rather low and ranges from 0 to €50/ha depending on the intensity of the drought. However, for a mature stand, the CSV rapidly increases, up to a maximum the year before the optimal harvest date. In this latter case, the CSV may be as high as €4900/ha for intense droughts.

Practical implications

A review of drought and heat-induced tree mortality by Allen et al. (2010) suggests that no forest type or climate zone around the world is invulnerable to such risks, even zones that are not considered as water-limited. However, forest owners cannot easily predict the time and the intensity of a drought since it occurs at random points in time and causes random-sized damages. For forest ecosystems, a drought results in both an increase in tree mortality and a reduction in tree growth. These impacts are delayed over time, usually begin to appear the year after the drought, and last for several years. The time gap between the observation of the climate event and its consequences makes it possible to adjust forest management practices and, in particular, to prematurely harvest the impacted stand and to replant a new stand if it is economically profitable to do so. In this study, we define a Climate Service (CS) as the information about the intensity of a drought event and its impacts on tree growth and mortality provided to forest owners just after a drought in order to help them decide to prematurely harvest (or not). For example, this CS could take the form of a combination of an eco-physiological model with an economic model linking climate and forest dynamics with economic outputs.

Estimating the economic value of this type of CS provides public institutions and decision-makers with an instrument to calibrate their investments in anticipation of a CS. In addition, as more and more private CS providers emerge, comparing the theoretical CS value with the willingness-to-pay of CS consumers makes it possible to better design the services exchanged on this market.

Using a comparison of Land Expected Values over an infinite period of forest rotations, our analysis suggests that the Climate Service Value (CSV) for a maritime pine stand undergoing a drought event is highly dependent on three characteristics:

(1) the age of the forest subject to the drought;
(2) the intensity of the drought both in terms of mortality and growth impacts;
(3) the value of the discount rate used.

Overall, for a 2% discount rate, we show that, for a young stand (less than 15-20 years old), the CSV is rather low and ranges from 0 to €50/ha depending on the intensity of the drought.

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https://doi.org/10.1016/j.cliser.2019.100106
Received 6 August 2018; Received in revised form 27 December 2018; Accepted 23 May 2019

However, for a mature stand, the CSV rapidly increases, up to a maximum the year before the optimal harvest date. In this latter case, the CSV can reach a maximum of €4900/ha for an intense drought.

These results suggest that a potential market for CS provision in the forest sector exists. In the case of drought, the main challenge for CS providers is to better assess the impacts of drought in terms of additional mortality and tree growth reduction. To tackle this challenge, mechanistic eco-physiological models are being developed (Bréda et al., 2006; Davi and Cailleret, 2017). One potentially important challenge for CS providers in the forest sector is to combine information on the impacts of climate events with economic information that can support forest managers in their decisions.

1. Introduction

In Western Europe, even under conservative scenarios, future climate changes are likely to come with larger winter rains, an increasing risk of winter storms and more severe precipitation deficits and heat waves during summer (Collins et al., 2013). Extreme heat waves and drought episodes like those experienced during summer 2003 in France, Germany and Spain are therefore expected to occur at increasing frequency. For forest ecosystems, a drought may result in both an increase in tree mortality and a reduction in tree growth. First, by limiting water availability, drought may induce large-scale tree growth decline (Bréda et al., 2006). Second, at some point, when the intensity of drought increases, this may result in the premature mortality of roots or twigs, and could ultimately lead to tree death (Battaglia et al., 1998; Le Dantec et al., 2000). The intensity of these impacts depends on the characteristics of the drought (duration, quantity and temporal distribution of precipitation), as well as to the combination of the drought with other climatic parameters (sunshine duration, relative humidity, mean and extreme temperatures) or with other climate-related disturbances such as pathogen invasion (Bréda et al., 2006; Caminero et al., 2018; Mina et al., 2016).

Importantly, these impacts are not immediate but are delayed over time, with an increase in mortality observed during the very first years after the drought (Renaud and Nageleisen, 2005; Vennetier et al., 2007), whereas tree ring width and leaf area are frequently smaller for several years following a severe drought (Caminero et al., 2018; Mina et al., 2016). This time gap between the observation of the climate event and its consequences makes it possible to adjust forest management practices and, in particular, to prematurely harvest the impacted stand and to replant a new stand if it is economically profitable to do so.

In forestry, climate services (CS) can support this kind of decision by taking the form of recommendations concerning initial plantation densities, choices of new species or species mixes, changes in rotation lengths or landscape planning for the purpose of minimizing fire and insect damage (Easterling et al., 2007). In particular, the existence and the quality of information to support the decision to change the rotation length in order to reduce economic losses are precious for forest managers. However, the economic value of this type of CS is rarely estimated and, to our knowledge, there is no example for forest activities in the literature. Yet, estimating this value could provide public institutions and decision-makers with an instrument that would allow them to better calibrate their investments in the supply of CS for the forest sector. Meanwhile, as more and more private CS providers emerge, comparing the theoretical CS value with the willingness-to-pay of CS consumers makes it possible to better design the services exchanged on this market.

In this study, we propose to estimate the value of CS in the case of a drought for a monospecific maritime pine forest in the Landes region in Southwestern France, as shown on Fig. 1. In this case, the CS consists of the information provided to forest owners about the timing and the intensity of the drought, both in terms of increases in mortality and growth decline. We compare two scenarios: one where CS are available and the other where they are not. The numerical results suggest that for an average 2% discount rate, the CS ranges between €0–50/ha for a young forest stand and between €0–4900/ha for a mature forest stand close to its optimal year of harvesting.

The article is structured as follows. In Section 1, we provide a literature review of climate services in the agricultural sector. Since no study dealing with CS value assessment in forestry was found, this literature review investigates the possibility of adapting methods developed in agriculture to the forest sector. We then describe the model developed in our framework in Section 2. In Section 3, we present the results and the analysis, discuss them in Section 4, and provide a conclusion in Section 5.

2. Review: the economic value of climate services in agriculture and forestry

In the agriculture sector, CS may take the form of raw climate observations and projections, climate indices (days of frost, length of a heatwave), and information such as mean temperatures (Vaughan and Dessai, 2014). They can also encompass adaptation solutions or advice regarding the best practices to adopt (Street, 2016). The economic literature extensively explores the concept of the expected value of information. Assuming that the information is perfect (i.e., predicted climatic conditions before decision-making will occur), the expected value of the information and, therefore, the value of CS are defined as the difference between the expected value of an optimal action with information and the expected value of an optimal action without information. In this vein, Mjelde et al. (1988) focused on the value of seasonal climate forecasts in corn production, defined as the difference between the expected net returns when the information is used optimally and when no additional information is used. They showed that a less accurate forecast received earlier in the production process might be more valuable than a more accurate forecast received later. However, as Runge et al. (2011) point out, information is rarely perfect. Several sources of uncertainty may arise and the relative importance of the different sources of uncertainty can be tested in order to decide which factor is more important to focus on. Hilton (1981) proposed to take these uncertainties into account by defining the expected value of the information as the difference between the expected utility of the agent using the weather forecast distribution and the expected utility of the agent according to the climatic conditions of the past. However, this method assumes that users have complete knowledge of historical climate conditions, which is highly unlikely.

To assess the economic consequences of climate arising from various El Niño–Southern Oscillation (ENSO) phases, Adams et al. (2003) developed a stochastic price-endogenous economic model for Mexico that accounts for changes in cropping patterns, production and consumption arising from the yield changes under each ENSO phase forecast. They show that the benefits of an ENSO early warning system for Mexico are approximately US$ 10 million annually, based on a 51-year time period of ENSO frequencies when a forecast skill of 70% is assumed.

Similarly, Roudier et al. (2012) computed the economic value of seasonal climate forecasts for millet producers in Nigeria according to the simulated yields derived from the different management strategies under different types of forecasts (imperfect, perfect and perfect with rainy season onset and offset dates). More recently, Lechthaler and Vinogradova (2017) estimated the value of CS for the coffee sector in Peru using a stochastic life-cycle model of a rural household that faces uncertainty with respect to the timing and the size of an adverse weather shock. In their paper, the one-year time horizon is divided into two sub-periods. In the first period, farmers receive an income that is either consumed or saved for precautionary measures against future coffee rust. In the second period, the savings are invested in the precautionary measure as the climate event occurs. The farmer's profit is

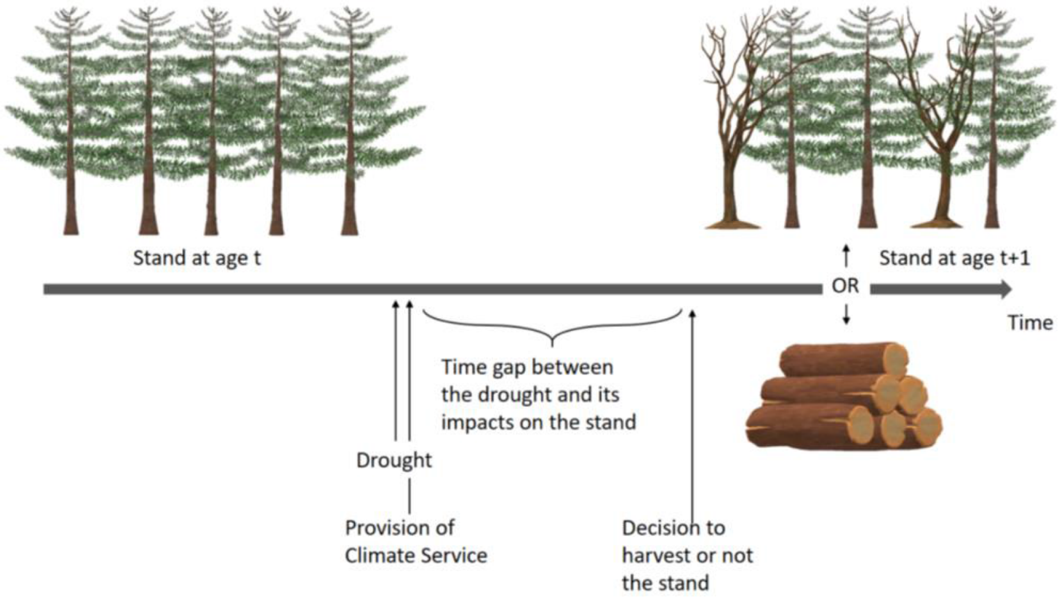

Fig. 1. . The Climate Service (CS) considered in this paper consists of the economic information provided by a model (or a set of models) to help forest owners to decide whether or not it is better to harvest the stand before the consequences of the drought occur. The CS is not about the date of occurrence of a drought, which we consider to be unpredictable, but about the intensity of its impacts in terms of an increase in mortality and a reduction in growth and, subsequently, about the value of the forest stand itself.

then impacted according to the timing of the occurrence of the weather shock, its intensity and the amount of the savings. The value of climate service is defined as the error made by the decision-maker between his discounted welfare with climate services (no uncertainty) and the one expected under uncertainty.

One missing feature of these studies is the treatment of multiannual systems such as forests. One important strategy to adapt to climate change in multiannual systems is to modify the rotation length. For example, by harvesting the trees just before the consequences of a climate event occur, forest owners can reduce their economic losses. For a climate event such as a storm, the event and its impacts on the forest stand are concomitant. In that case, it is impossible to adjust the forest rotation length. However, for other events such as a drought or a pathogen invasion, there is a time gap between the onset of the event and its physical consequences on the forest stand. In this latter case, the forest owner can deliberately choose to prematurely harvest and to replant or to leave the forest standing. This choice is likely to depend on the age of the forest and on the intensity of the climate event. In the subsequent sections, we develop a methodology to explore this issue.

3. Material and methods

We define the CS as the climate information related to the date of occurrence and the intensity of the climate event. We define the intensity as the potential growth reduction and rise in mortality in the forest stand. Following Lechthaler and Vinogradova (2017) and Adams et al. (2003), we developed a methodology based on the comparison between a situation with CS and a situation without CS. In order to deal with the multiannual time horizon, we used the forest's Land Expectation Value (LEV), i.e., the Faustmann (1849) criterion, as an economic value index between scenarios. The LEV is the present value, per unit area, of the projected costs and revenues from an infinite series of identical even-aged forest rotations, initially starting from bare land. It assumes that each rotation is of equal length, that the sequence of events within each rotation is the same, and that the net revenue associated with each event within a rotation is similar for all rotations. Contrary to other economic criteria such as the Net Present Value or the Discounted Profit, using the LEV makes it possible to compare the values of projects of different lengths, which is precisely what we want to do here.

3.1. The model

We use the standard LEV model in the case of even-age stands with constant discounted rate and prices over time. To simplify, we assume there are only two silvicultural operations during the rotation: plantation and final harvest.[1]

We define the Climate Service Value (CSV) as the difference between the LEV with CS and the LEV without CS.

$$CSV = LEV_{CS} - LEV_{noCS} \tag{1}$$

where:

$$LEV_{CS} = \frac{R(T_{CS})e^{-rT_{CS}} - D(0)}{1 - e^{-rT_{CS}}} \tag{2}$$

and:

$$LEV_{noCS} = \frac{R(T)e^{-rT} - D(0)}{1 - e^{-rT}} \tag{3}$$

These equations are the so-called Faustmann formula (Reed, 1984; Clark, 1976). The left component of the numerator in (2) and (3) is the revenue derived from the final harvest, whereas the right component consists of the initial plantation costs. In detail:

- T is the optimal harvesting age without climate service and T_{CS} is the optimal harvesting age with climate service.
- $R(T_{CS})$ is the revenue from selling trees at age T_{CS}, where $R(T_{CS}) = V(T_{CS}) \times p(v(T_{CS}))$
  - o $V(T_{CS})$ is the total volume per ha: $V(T_{CS}) = v(T_{CS}) \times q(T_{CS})$, where$v(T_{CS})$ is the unitary tree volume in m^3 at age T_{CS} and $q(T_{CS})$ is the number of trees at age T_{CS} in trees/ha. Similarly, $v(T)$ is the unitary tree volume in m^3 at age T, $V(T)$ is the total volume per ha, and $V(T) = v(T) \times q(T)$, where $q(T)$ is the number of trees at age T in trees/ha.
  - o $p(v(T_{CS}))$ is the price in €/m^3 for a unitary volume $v(T_{CS})$. Making

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[1] In particular, we assume there is no other forest operation such as thinning.

the price dependent on the unitary tree volume assumes that the type of wood use depends on the size of the trees. Schematically, the biggest trees are expected to be used in the roundwood transformation industries and sold at higher prices, whereas the thinnest are expected to be used as industrial or energy wood and sold at lower prices.

- $D(0)$ is the initial plantation cost and is the discount rate.

3.2. *Optimal rotation ages with and without climate services*

The forest owner's problem is to determine the age that maximizes the forest's LEV, i.e., to find the date t such that:

$$\frac{\partial LEV}{\partial t} = 0 \Longleftrightarrow \frac{\partial R(t)}{\partial t} = r(LEV + R(t)) \tag{4}$$

This equation can be interpreted as equating the marginal benefit of waiting for an additional year before harvesting $\left(\frac{\partial R(t)}{\partial t}\right)$ with the sum of the interest costs of postponing the next harvest ($r \times R(t)$) plus the interest costs of postponing all the subsequent harvests ($r \times LEV$) (Reed, 1984).

Now, let us assume that a drought (designated CC for *"Climate Change"*) occurs and impacts both tree growth through the unitary volume v_{CC} and tree mortality through the number of trees q_{CC}. The forest owner's problem with CS is then expressed as:

$$\frac{\partial LEV_{CS\_CC}}{\partial T_{CS\_CC}} = 0 \Longleftrightarrow \frac{\partial R_{CC}(T_{CS\_CC})}{\partial T_{CS\_CC}} = r(LEV_{CS\_CC} + R_{CC}(T_{CS\_CC})) \tag{5}$$

where $R_{CC}(T_{CS\_CC}) = v_{CC}(T_{CS\_CC}) \times q_{CC}(T_{CS\_CC}) \times p(v_{CC}(T_{CS\_CC}))$

Whereas the same problem without CS is expressed as:

$$\frac{\partial LEV_{CC}}{\partial T} = 0 \Longleftrightarrow \frac{\partial R_{CC}(T)}{\partial T} = r(LEV_{CC} + R_{CC}(T)) \tag{6}$$

$$R_{CC}(T) = v_{CC}(T) \times q_{CC}(T) \times p(v_{CC}(T))$$

Eq. (5) implies that if the forest owner receives the climate service, she/he will adjust the optimal age of rotation T_{CS_CC}depending on the impacts of the drought CC over the unitary volume $v_{CC}(T_{CS\_CC})$ and the number of trees $q_{CC}(T_{CS\_CC})$. In the case where the forest owner does not receive a climate service (Eq. (6)), the forest stand still undergoes the same drought CC, (i.e., v_{CC} and q_{CC} are the same as in Eq. (5)) but the forest manager is shortsighted and acts as if there were no drought by conserving the optimal harvest age without the climate service T.

In both cases, we assume that the drought occurs at the same date and with the same intensity. However, the optimal harvesting age is likely to be different since the forest owner with CS will adapt the rotation length accordingly.

To summarize, CSV is the difference in the LEV of the following two scenarios:

Scenario CS_CC:	Scenario CC:
• Forest owner has no information about the incidence of a drought at the beginning of the rotation • Drought incidence takes place • Forest owner has information about the impacts of the drought, just after the incidence • Optimal rotation age T_{CS_CC} is modified	• Forest owner has no information about the incidence at the beginning of the rotation • Drought incidence takes place • Forest owner has no information about the impacts of the drought • Optimal rotation age T remains the same as without a drought incidence

4. Modeling the impacts of a drought

4.1. *Modeling plan*

To solve Eqs. (5) and (6), we model$v_{CC}(t)$, $q_{CC}(t)$ and $p(v_{CC}(t))$ for a maritime pine stand in Southwestern France. We present the modeling and calibration processes in Appendix 1.

Table 1
Values of the parameters tested.

Parameter	Definition	Range of values tested	Step
r	Discount rate	0.01–0.03	0.005
φ	Date of occurrence	1–32	1
s	Additional mortality rate	0.2–0.5	0.1
h	Rate of growth decline	0.2–0.5	0.1

We then choose to estimate the impacts of the drought CC on the forest stand by varying three parameters: φ is the year of occurrence of the impacts of the drought on the forest stand, s is the additional mortality rate (in %), and h is the rate of growth decline. If a drought occurs at year φ, $\Delta v_t = v_t - v_{t-1}$ is modified such that $\forall\ t \geq \varphi \Delta v_{CC}(t) = \Delta v_t \times (1 - h)$ and q_t is modified such that as $\forall\ t \geq \varphi q_{CC}(t) = q_t \times (1 - s)$.

We compute the optimal rotation ages (i.e., we solve Eqs. (5) and (6)) using Julia software.[2] We then compute the CSV by subtracting the LEV with and without CS, as mentioned in Eq. (1).

We calculate the CSV for a range of these three parameters and by varying the discount rate (Table 1) . This results in 4000 simulations.

4.2. *Results: optimal age of rotation*

Without a climate event, (i.e., $s = 0$, $h = 0$, $\varphi = \emptyset$), the optimal year of harvesting derived from Eq. (4) is $T = 32$ years for $r = 2\%$.

Now, if a drought takes place and if the forest owner receives the climate service, the optimal age of rotation changes according to the values of s, h and φ, as presented in Fig. 2.

Fig. 2 shows that the optimal harvesting age with climate services T_{CS_CC} depends on the date of occurrence of the climate eventφ . We distinguish two ranges of values for φ with different implications and we define a threshold value for φ that we refer to as $\bar{\varphi}$.

For$\varphi < \bar{\varphi}$, we have $T_{CS\_CC} > T$ (solid blue line above red dotted line on Fig. 2), i.e., when the drought occurs at the beginning of the forest stand life, knowing the consequences of the drought on the stand dynamics tends to postpone the optimal harvesting age. This is because when the drought occurs early in the forest stand life, the cumulated standing capital is low and the profit made by harvesting and selling it would not compensate for new plantation costs. Therefore, the optimal economic option is to keep the impacted forest standing and conduct it up to age T_{CS_CC} when the forest volume will be big enough to generate sufficient revenue. We can observe on Fig. 1 that in this case, T_{CS_CC} decreases when φincreases: the earlier the climate event occurs, the later the age for which the forest volume will be big enough to be harvested. This is due to two factors. First, we assume that the growth reduction is permanent as of the date of the drought, which implies that the earlier it happens, the higher the cumulated growth loss would be. Second, the younger the trees are, the higher their growth rate is (see Fig. 7 in the Appendix) and, therefore, the greater the impact of a growth reduction. For the very same reasons, all other things being equal, increasing h or s postponesT_{CS_CC}.

For $\bar{\varphi} \leq \varphi \leq T$, we have $T_{CS\_CC} < T$. At that point, the forest owner's optimal strategy completely changes since it is now economically profitable to harvest the stand just after the drought but before the impacts of the drought on the stand occur in order to start a new forest stand from bare land once again. This threshold value $\bar{\varphi}$ appears quite early, between 15 and 20 years of age in our simulations, depending on the values of h and s. Increasing either h or s (or both) moves forward the threshold value $\bar{\varphi}$ and therefore reducesT_{CS_CC}, contrary to what happens for $< \bar{\varphi}$.

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[2] https://julialang.org/.

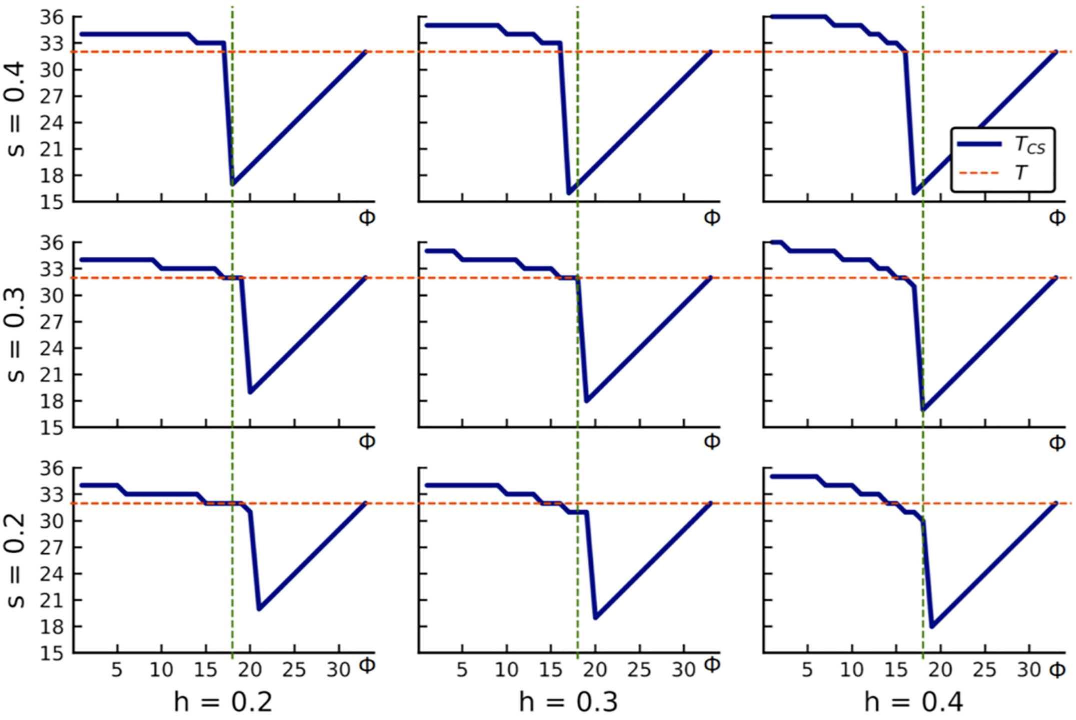

Fig. 2. . Optimal harvesting ages when the forest owner obtains the climate service. For each chart, the x-axis indicates the date of the occurrence φ (the green dotted line refers to φ = 17 years as a benchmark for all the scenarios), and the y-axis indicates the optimal harvesting age with climate services T_{CS_CC} (solid blue line), where the red dotted line refers to T = 32 years. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4.3. Results: climate service value

Once we obtainT_{CS_CC}, we can compute the LEV_{CS} (Eq. (3)) and LEV_{noCS} (Eq. (4)) to obtain the climate service value CSV (Eq. (1)).

Fig. 3 shows the variations in the CSV for r = 3%, s = 0.3 and h = 0.3.

We can once again distinguish two trends of results regarding the date of occurrence φ:

For $\varphi < \bar{\varphi}$, the CSV is low and decreases with φ. In that case, as explained in the previous section, the forest owner adapts by adjusting the optimal harvest age to $T_{CS\_CC} > T$. As φ increases and moves towards$\bar{\varphi}$, the harvest is less and less postponed and the T_{CS_CC}value moves towards the$T$ value. As a consequence, LEV_{CS} progressively moves towards LEV_{noCS} up to $\bar{\varphi}$, where $T_{CS\_CC} = T$ and $LEV_{CS} = LEV_{noCS}$. At that point, $CSV = 0$.

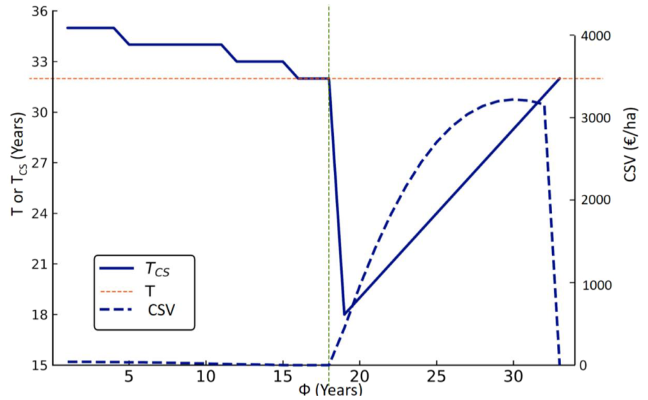

Fig. 3. . Climate service value CSV and optimal harvesting age in the case {r = 3%; h = 30%; s = 30%}. The x-axis indicates the date of φ, the left side of the y-axis indicates the optimal year of harvesting, and the right side of the y-axis indicates the CSV in €/ha. The green dotted line refers to$\bar{\varphi}$ = 18 years, whereas the red dotted line refers to T = 32 years. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

For $\bar{\varphi} \leq \varphi \leq T$, the CSV increases with φ since the value of the stand and, consequently, the value of the expected loss due to the drought increases as the stand ages.[3] In other words, the later the climate event occurs in the life of the stand, the higher the CSV will be.

Fig. 4 shows the variations in the CSV for s, h and the discount rate r. Three main results can be derived from this figure.

First, increasing h or s, all other things being equal, increases the CSV. This is rather intuitive and means that the value of climate services increases with the intensity of the drought. However, the relative importance of s and h differs according to the date of occurrence of the drought φ. A decline in the growth rate relatively affects the CSV value more than a rise in the mortality rate for early φ, whereas the opposite holds for late φ. This is because an additional mortality has the same impact regardless of the age of the stand. However, since the marginal growth is higher for young trees and tends to an asymptote as the stand matures (Fig. 9 in Appendix 2), an early drought will have a relatively greater impact on growth than a later one.

Second, the CSV is highly sensitive to the discount rate value. This is visible on Fig. 5 for a 1% increase in r and for several values of s and h. The discount rate r affects both the optimal harvesting age and the absolute CSV value. In addition, a higher discount rate gives a relatively greater importance to an early drought and less importance to a late one (see Fig. 10 in Appendix 2).

Third, when testing “reasonable” values for s, h and r, the CSV ranges from 0 to €4900/ha depending on the value of φ, s, h and r. However, we observe a large discrepancy of the CSV regarding the date of occurrence of the drought. When the drought occurs before $\bar{\varphi}$, the CSV remains low and ranges between €0-50/ha. However, when drought occurs after $\bar{\varphi}$,therefore affecting an almost mature stand, the CSV is much higher and ranges between €0–4900/ha in our

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[3] v increases and so does V and p(v).

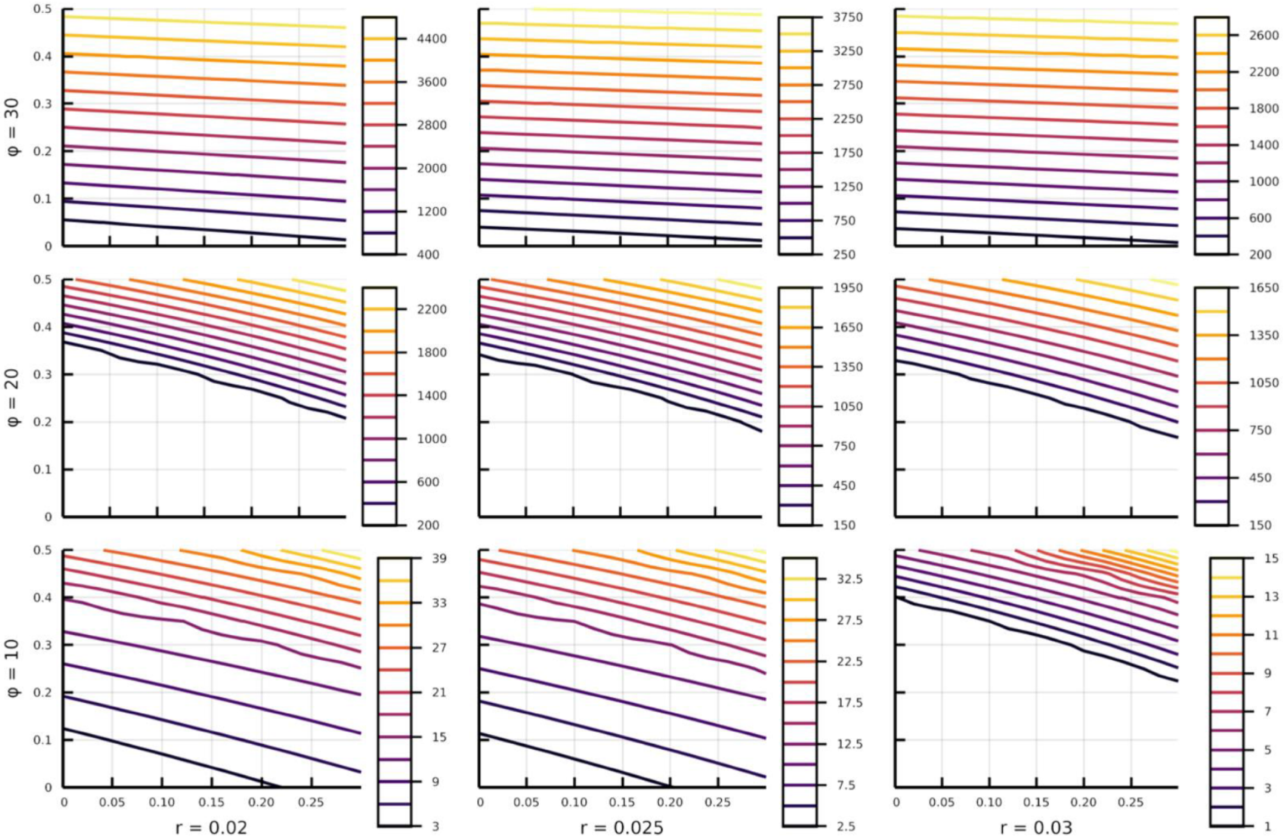

Fig. 4. Climate service values (CSV) for different r, φ s and h. For each chart, the x-axis indicates h and the y-axis indicates s. Colored contour lines indicate the climate service values in €/ha.

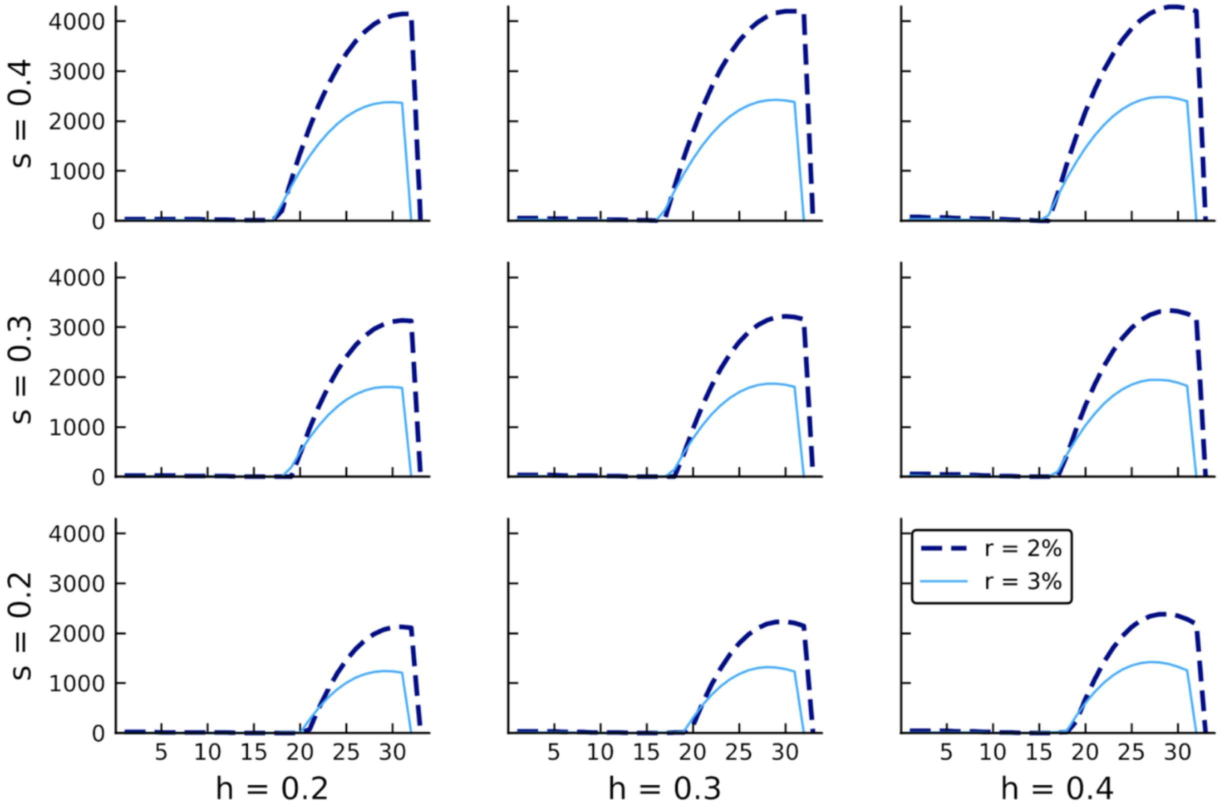

Fig. 5. Impact of the discount rate r on the CSV (y-axis: CSV in €/ha; x-axis: date of φ).

simulations. Consequently, the forest owner's willingness-to-pay for CS is likely to be non-linear regarding the age of the impacted stand, i.e., while it remains low for young stands, it rapidly increases as stands mature. One direct implication is that investments for CS should focus on mature forest areas.

5. Discussion

Our study is a first important step in defining a methodology to estimate the CSV in forestry. We propose four possible future research paths here to improve and expand our methodology.

First, relying on the Faustmann model leads us to assume an infinite rotation sequence with a drought occurring at the same age during the future rotations. In addition, using the Faustmann framework requires constant parameter values over time. One possible improvement consists in making these parameters dynamic. This point is extensively discussed in the literature. For instance, Buongiorno and Zhou (2011) worked on a Faustmann model with stochastic prices and discount rates. Price (2011, 2017) tested different discount rates patterns over time, whereas Chang and Gadow (2010) extended the Faustmann model to uneven-age stands. In particular, it is likely that a risk-averse forest owner suffering from a drought during the first rotation will change her/his behavior for the second rotation, even without a climate service. For this purpose, Chang (1998) proposes a generalization of the Faustmann formula that allows the harvest age to vary from timber crop to timber crop by varying the stumpage price, timber yield, regeneration cost and interest rate. However, empirical studies show that forest owners are usually risk-prone or risk-neutral (Andersson, 2012). A recent study by Brunette et al. (2017) shows that French forest owners are characterized by a relative risk aversion coefficient close to 1, i.e., they are risk-neutral. In addition, the length of rotation makes the "learning-by-doing" process limited in the forest sector since one individual forest owner might experience only one forest rotation during his/her active life.

Second, we assumed that growth decline is permanent as of the date of drought. In reality, trees undergo a time of recovery that depends on several factors: climate and carbon cycle dynamics, with biodiversity and CO_2 fertilization as secondary factors (Schwalm et al., 2017). Data presented in Schwalm et al. (2017) suggest that the current average time of recovery for the Landes forest ranges between one and two years. Yet, their model shows that given the changes in temperature as well as the increases in drought frequency and severity projected for the 21st century, terrestrial ecosystems will take longer to recover after droughts.

Third, we modeled the impacts of a single drought on growth and mortality during one rotation without considering the implications of multiple droughts during one forest rotation. In particular, do multiple droughts lead to a permanent growth decline with/without additional mortality or do they increase both growth decline and mortality? Bréda et al. (2006) show that long-term tree mortality is a complex function of the interactions among depleted carbohydrate stores in trees, decreased water transport efficiency and pest and disease outbreaks that affect weakened trees. Multiple droughts could therefore both lead to additional growth decline and a rise in mortality (possibly in a non-linear way since trees already weakened by a prior drought could die with a less intense drought than healthy trees). To consider these impacts, further work would consist of linking our modeling framework to a mechanistic eco-physiological model that estimates the mortality risk of forest trees under global change. One example is Davi and Cailleret (2017) who use the CASTANEA model to simulate the development of tree functioning over time with different ontogenetic and phenotypic characteristics (age, diameter, Leaf Area Index, leaf traits) and that grow in different site conditions (elevation, soil water content).

Fourth, the combination of several climate events could make the CSV estimation even more challenging. Bréda et al. (2006) suggest that the consequences of a drought are more severe for trees already weakened by previous incidents such as storms, and the effects of such climatic accidents can occur more than 10 years later. In this vein, Manion (1981) assumes that there is a three stage decline over many years: a long-term stress, a short term one like drought, and then death, occurring via a vector such as pathogens since climate change induces demographic changes that increase the number of pathogens (McDowell et al., 2008; Rouault et al., 2006).

6. Conclusion

Using a comparison of Land Expected Values, our analysis suggests that the Climate Service Values (CSV) for a maritime pine stand undergoing a drought is highly dependent on the age of the stand, on the intensity of the drought in terms of mortality and growth impacts and on the discount rate used. Overall, for a 2% discount rate, we show that for a young stand (less than 15–20 years old), the CSV is rather low, ranging from 0 to €50/ha. However, for a mature stand, the CSV rapidly increases, up to a maximum the year before the optimal harvest date. In the latter case, in the event of an intense drought, the CSV can reach €4900/ha.

The agricultural economics literature suggests that the CSV for coffee plantations in Peru ranges between $17–28/ha (Lechthaler and Vinogradova, 2017). For maize, Bert et al. (2006) estimate the economic value of climate information at between $20–30/ha, with peaks at $320/ha corresponding to the occurrence of ENSO phenomena. In addition, when reviewing surveys about the economic value of seasonal climate forecasts for agriculture, Meza et al. (2008) reported that the CSV considerably increases with risk aversion up to a certain point at which the agent is so risk-averse that he does not trust the weather forecasts, which are too uncertain. Our results do not directly compare with these findings since we compute the CSV for an infinite number of forest rotations, whereas agriculture studies calculate the values for one year. The annuity corresponding to a LEV of €4900 using a discount rate of 2% is 4900 * 0.02 = €98/ha/year. It appears that this value is still higher than the values given in the agricultural economics literature. One interpretation is that in the case of a forest, the drought destroys a capital that was built up over several years, whereas in agriculture, a climate disaster "only" ruins one year of production.

Moreover, in our case study, the values for s and h remain theoretical and disconnected from observations. In order to compute the CSV for a specific drought, it is necessary to rely on dendrochronological and inventory observations, which make it possible to estimate h and s. Allen et al. (2010) reviewed several studies that estimate tree mortality after the 2003 drought. It appears that mortality rates are highly dependent on the species and the location, and range between 0.8% and 80%. For France specifically, Renaud and Nageleisen (2005) estimate the tree mortality following the 2003 summer drought at 1.2% for conifers at the national scale. The impact of drought on growth reduction is even more heterogeneous between forests and within a specific forest. Exploring the impacts of the 1994–1995 drought on Aleppo pine in Spain, Gazol et al. (2017) show that on 27 observation sites, 88% of the trees showed a growth reduction of about 60% the year after the drought. The values presented in Fig. 3 are therefore rather conservative and show an intermediate level of impact on growth reduction.

Eventually, our method could apply in many other situations. Indeed, the significance of the Faustmann formula and its conditions is not restricted to forestry. As pointed out by Gaffney (2008), the Faustmann formula ostensibly deals with timber growth but can be adapted to deal with all capital assets and with any time patterns of inputs and outputs whatsoever. When restricted to the forestry field, our methodology is likely to apply to any events (climate-related or not) that have time-delayed impacts, making it possible to adjust the forest rotation length. This could be the case for several forest pathogens (*Heterobasidion annosum* or *Thaumetopoea pityocampa,* for example, in the case of maritime pine).

Declaration of Competing Interest

None.

Acknowledgments

This work was funded by the European project MARCO-730272 (MArket Research for a Climate Services Observatory) of the Horizon 2020 program. The BETA contributes to the French project Labex ARBRE ANR-11-LABX-0002-01. The authors thank Jemma Lemarchand for her valuable work.

Appendix 1:. Model calibration

To solve Eqs. (5) and (6), we need to model $v_{CC}(t)$, $q_{CC}(t)$ and $p(v_{CC}(t))$. To do that, we start from an observed silvicultural standard defined by the *Société Forestière de la Caisse des Dépôts et Consignations* (Table 2). This standard is made for a monoculture of maritime pine in the Landes de Gascogne Forest. It refers to a plantation of 1000 seedlings/ha with two thinnings performed at years 13 and 23, and a final harvest at year 35. We assume the two thinnings to be cost-neutral, so that the only expenditure is the initial plantation cost at year 0 with D(0) = €700/ha.

Table 2
Sylvicultural standard defining forest operations and dynamics as given by the *Société Forestière de la Caisse des Dépôts et Consignations*.

age	*qstd*	*vstd* (m^3/tree)	age	*qstd*	*vstd* (m^3/tree)
1	1000		19	487	0.31
2	1000		20	485	0.34
3	1000		21	483	0.38
4	1000		22	480	0.42
5	1000		23	321	0.5
6	1000		24	320	0.55
7	1000		25	319	0.6
8	1000		26	318	0.64
9	1000		27	317	0.69
10	1000		28	315	0.74
11	997	0.06	29	313	0.79
12	994	0.07	30	311	0.83
13	496	0.11	31	309	0.88
14	495	0.14	32	307	0.93
15	494	0.17	33	305	0.97
16	493	0.2	34	303	1.02
17	491	0.24	35	301	1.07
18	489	0.27			

In practice, two thinnings are planned in order to both "concentrate" the timber volumes on a smaller number of individuals and to allow a dense initial plantation, which, in turn, favor slim logs with few intermediate branches and knots. On the basis of this standard, our "data crunching" objective is to obtain the dynamics of the forest in terms of the number of trees and volumes, *as if* the two thinnings are not performed and when the final harvesting age is not chosen *ex ante*. In other words, we aim at defining a "natural" dynamics of the planted forest.

For this, two main assumptions are made: (a) the evolution of the stand, measured through its mass (proxied by the inventoried volumes) in the absence of thinning would follow a logistic curve; and (b) thinning does not have any effect on the total growth and mortality at the stand level.

To do that, we start computing the survival rate on the basis of the number of trees in the silvicultural standard:

$$survRate_t = \frac{qstd_t}{qstd_{t-1}} \tag{7}$$

We then interpolate the series (excluding the two years of thinning) to obtain the "natural" survival rate *natSurvRate* (intercept: 0.99987; slope: -0.000185 – Fig. 6) that we used, in turn, to (a) compute the dynamic of trees q_t that would have survived in the stand if thinnings were not performed; and (b) to decompose the "naturally dead trees", distinct from the removed (thinned) trees in the observed variation in the number of trees in the years of thinning.

Removed "thinned" trees are computed as:

$$qr_t = qstd_t - qstd_{t-1} - natSurvRate_t * qstd_{t-1}$$

Modeling V_t and v_t

On the basis of the number of trees thinned, we computed the volume removed $Vr_t = qr_t * vstd_t * c_t$, where c_t is an adjustment coefficient, in order to take the possibility that thinned trees may have lower-than-average volumes into account (we used the coefficients 0.65 and 0.7 for the two thinnings).

The stand volumes that would exist without thinning are computed as the volumes given by the silvicultural standard with thinning, plus all the removed volumes:

$$Vnothinnings_t = qstd_t * vstd_t + \sum Vr_j$$

Once we obtained $Vnothinnings_t$, we then used the Julia Package LsqFit[4] to estimate a generalized logistic model:

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[4] John Myles White, LsqFit Julia package, v 0.3.0, https://github.com/JuliaNLSolvers/LsqFit.jl.

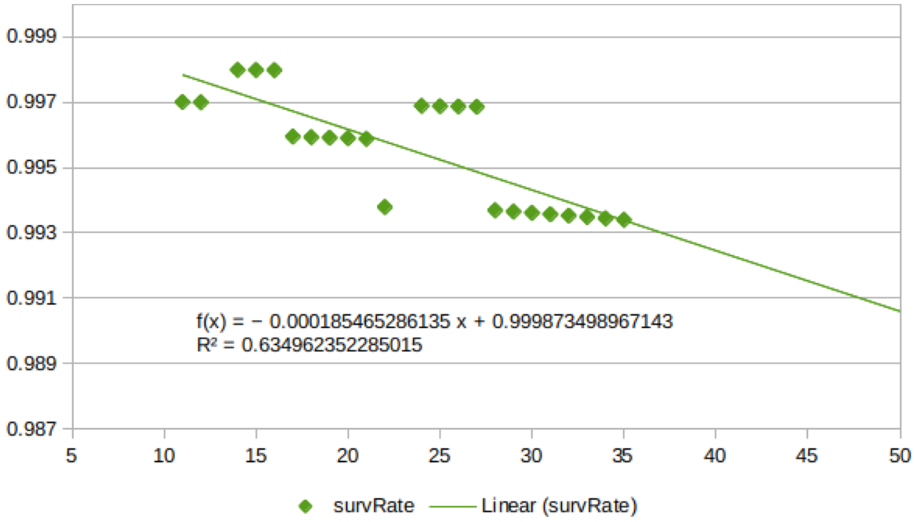

Fig. 6. Observed and estimated tree survival rate.

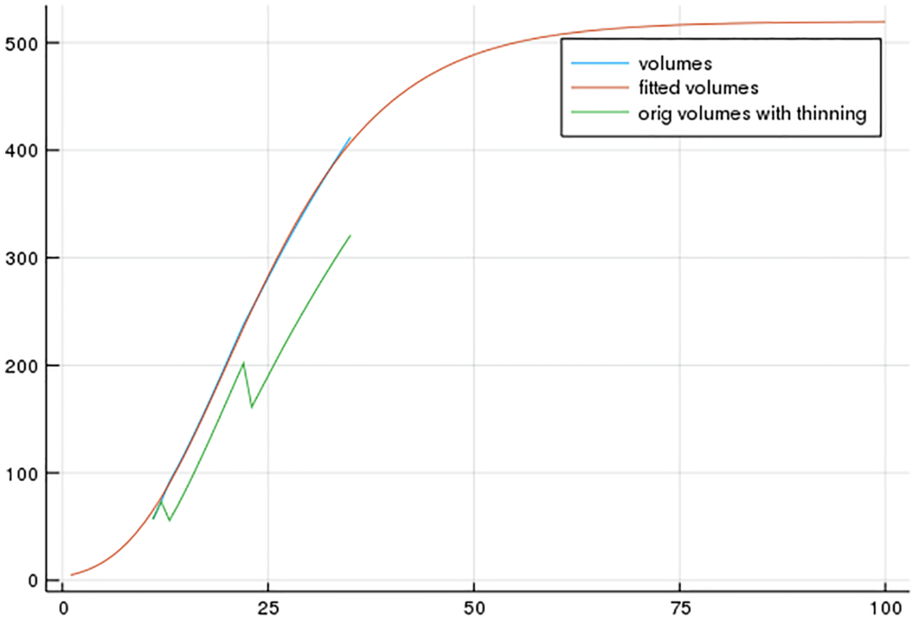

Fig. 7. Comparison between forest volumes (with thinning) from the standard and computed volumes without thinning.

Table 3
Stumpage prices per log volume class as computed with the fitted logarithmic model.

v m^3/tree	p €/m^3	v m^3/tree	p €/m^3	v m^3/tree	p €/m^3
0.05	10	*1*	30.5	*2*	34.74
0.1	13.63	*1.1*	31.2	*2.1*	34.96
0.2	18.71	*1.2*	31.84	*2.2*	35.16
0.3	21.68	*1.3*	32.42	*2.3*	35.33
0.4	23.79	*1.4*	32.97	*2.4*	35.47
0.5	25.42	*1.5*	33.17	*2.5*	35.6
0.6	26.76	*1.6*	33.56	*2.6*	35.7
0.7	27.89	*1.7*	33.91	*2.7*	35.79
0.8	28.86	*1.8*	34.22	*2.8*	35.86
0.9	29.73	*1.9*	34.5	*2.9*	35.92
				3	35.96

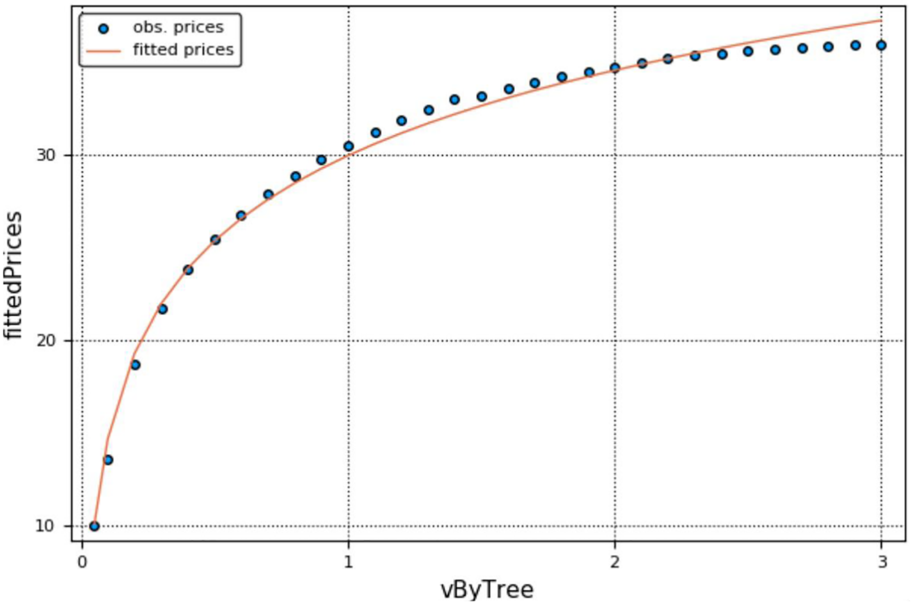

Fig. 8. Observed and fitted timber prices per log volume.

$$V_t = \frac{K}{(1 + e^{-B(t-M)})^{\frac{1}{G}}} \tag{8}$$

obtaining the parameters K, B, M and G (519.7, 0.0926, -6.44 and 0.0874, respectively).

We then computed $v_t$as $v_t = V_t/q_t$.

Modeling$\boldsymbol{p}(\boldsymbol{v_t})$

Timber prices are highly dependent on log size since the array of possible uses increases with size. We obtained the standing timber market price (stumpage) for each log's volume class (Table 3) from the *Société Forestière de la Caisse des Dépôts et Consignations.*

Using the LsqFit[1] package once again, we fitted the prices according to a logarithmic model (Fig. 8) with parameters 29.939 and 6.631 for the fixed and logarithmic terms, respectively.

Appendix 2: Relative importance of s, h and r on the CSV

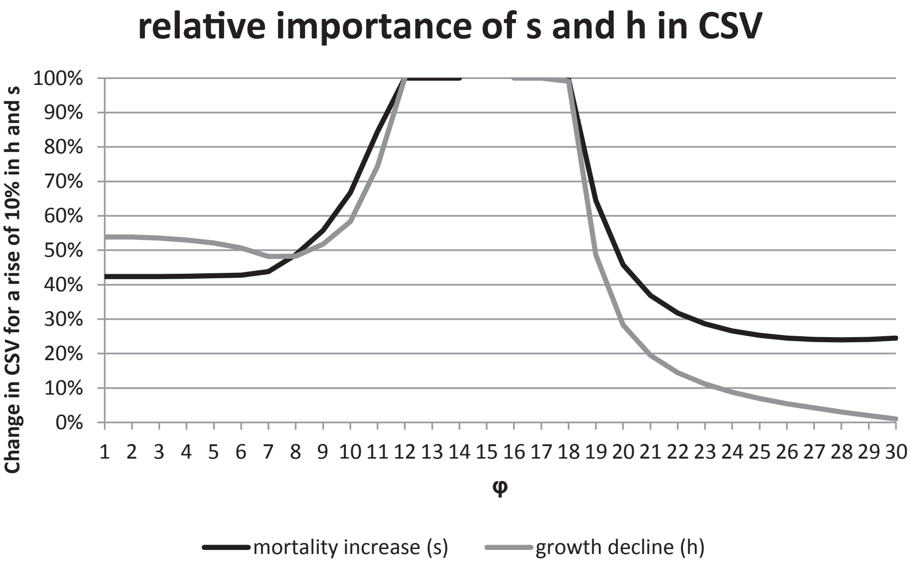

Fig. 9. Relative importance of a change in s and h in the CSV value according to the date of the climate event φ.

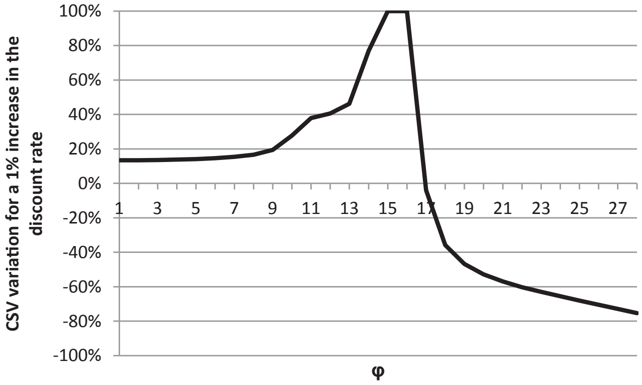

Fig. 10. . CSV variation for a 1% increase in r, according to the date of the climate event.

Appendix 3:. Supplementary material description

This article is accompanied by a supplementary material archive containing the following items:

- **input_data.ods** is the input data for the simulations, including *q(age)*, *v(age)* and *p(v)* for the studied maritime pine stand, in OpenDocument format;
- **model_code.{jl|pdf}** is the modeling code using to produce the simulations, written in the Julia language;
- **sim_results.ods** includes the full output of our simulations, i.e., (LEV_{CS}, T_{CS}, CSV) as a function of (r, φ, h, s), also in OpenDocument format.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cliser.2019.100106.

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