Annals of Forest Science (2021) 78: 57
https://doi.org/10.1007/s13595-021-01071-2

RESEARCH PAPER

Assessing the land expectation value of even-aged *vs* coppice-with-standards stand management and long-term effects of whole-tree harvesting on forest productivity and profitability

Abdelwahab Bessaad[1,2] · Jean-Philippe Terreaux[1] · Nathalie Korboulewsky[2]

Received: 12 June 2020 / Accepted: 13 May 2021 / Published online: 21 June 2021

Abstract

• ***Key message*** **Whole-tree harvesting makes forests more profitable than conventional harvest as long as the impact on tree growth remains under 2.3% for even-aged oak (*Quercus petraea* (Matt.) Liebl.) and 3.4% for sweet chestnut (*Castanea sativa* Mill.) coppice with oak standards. Coppice-with-standards may have potential to be more profitable than even-aged oak in case of 50% rise in fuelwood prices with 10% decrease in timber prices.**

• ***Context*** Making the shift to renewable energy sources requires increasing biomass removal from the forest in a sustainable way. Today, the most common practice for forest biomass extraction is whole-tree harvesting rather than conventional harvest in which only stems are harvested or sometimes branches larger than 7 cm in diameter. However, intensive biomass harvesting can certainly increase economic profitability but it could affect long-term forest productivity because more nutrients are exported from sites.

• ***Aims*** We explored the land expectation value of even-aged oak (*Quercus petraea* (Matt.) Liebl.) and sweet chestnut (*Castanea sativa* Mill.) coppice with oak standards under different discount rates and wood prices scenarios, tree mortality triggered by climate variation as well as the effects of a decrease in forest productivity due to whole-tree harvesting on the land expectation value (LEV).

• ***Methods*** We modeled two plausible harvesting scenarios for both stands and assessed their LEV. We first analyzed the sensitivity of the valuation results to discount rate, wood prices changes, and increased tree mortality rates. Second, we compared conventional harvest to whole-tree harvesting in which removing the fine wood implies a decrease in tree growth over the long term (between 1 and 10%).

Handling Editor: Rasoul Yousefpour

Contributions of the co-authors Conceptualization: Jean-Philippe Terreaux, Nathalie Korboulewsky; Methodology: Abdelwahab Bessaad, JeanPhilippe Terreaux, Nathalie Korboulewsky; Software: Abdelwahab Bessaad; Validation: Abdelwahab Bessaad, Jean-Philippe Terreaux, Nathalie Korboulewsky; Formal analysis: Jean-Philippe Terreaux; Investigation: Abdelwahab Bessaad; Resources: Abdelwahab Bessaad, Jean-Philippe Terreaux, Nathalie Korboulewsky; Data curation: Abdelwahab Bessaad; Writing (original draft): Abdelwahab Bessaad; Writing (review and editing): Abdelwahab Bessaad, Jean-Philippe Terreaux, Nathalie Korboulewsky; Visualization: Abdelwahab Bessaad; Supervision: Jean-Philippe Terreaux; Project administration: Nathalie Korboulewsky; Funding acquisition: Nathalie Korboulewsky.

✉ Abdelwahab Bessaad
abdelwahab.bessaad@inrae.fr

Jean-Philippe Terreaux
philippe.terreaux@inrae.fr

Nathalie Korboulewsky
nathalie.korboulewsky@inrae.fr

[1] INRAE, UR ETBX, 50 Avenue de Verdun, Gazinet, F-33612 Cestas, France

[2] INRAE, UR EFNO, Domaine des Barres, F-45290 Nogent-sur-Vernisson, France

• ***Results*** In the current economic situation, the LEV of even-aged oak is higher than coppice-with-standards but this situation could be reversed in case of rising energy prices and lower timber prices in the future. The variation of the discount rate has a significant impact on the LEV but 3% seems to be adequate for European forests. A gradual increase in annual tree mortality rate of 0.6 and 0.9% along even-aged and CWS rotation, respectively, reduced the LEV by half, while increased mortality with constant rates along the rotations had more negative effect on the LEV than gradual increases: 0.4–0.5% increases in mortality rates reduced both LEV's by half.

Whole-tree harvesting is able to improve the LEV for both stands by 36 to 64% compared to conventional harvest; but this improvement of LEV only lasts as long as the impact on tree growth remains under 2.3 and 3.4%, respectively, for even-aged oak stand and coppice-with-standards.

• ***Conclusion*** Whole-tree harvesting system increases forest profitability as long as the sustainability guidelines for biomass harvesting are respected. With the increased demand for fuelwood, the coppice-with-standards regime may become financially attractive once again and fulfill a multitude of forest owner objectives with a wide range of additional options.

Keywords Fine wood · Fuelwood · Sessile oak · Chestnut coppice · Faustmann model · Optimal rotation length

1 Introduction

In the context of climate change, national and international institutions have recommended the promotion of renewable energy to protect the global environment and reduce greenhouse gas emissions. The new bioeconomy roadmap for European countries (European Commission 2018) aims to accelerate the deployment of a sustainable bioeconomy by promoting bio-based products and wood consumption for different uses to reach sustainable development goals respecting the Paris Agreement (UN General Assembly 2015). The strategies of the bioeconomy and forest-based sector focus intensively on production processes, product substitution by bio-based alternatives, and resource efficiency (Pelli et al. 2017). France has launched its national bioeconomy strategy (Alim'agri 2017) and has set operational objectives for the forest-based sector, detailed in the National Forestry and Wood Programme (PNFB) and the National Biomass Mobilization Strategy (SNMB) (Alim'agri 2016; MTES 2018). This forest policy aims to satisfy biomass demand in both volume and quality and to optimize the co-benefits of this mobilization while preventing potentially negative impacts.

However, the development of forest bioeconomy is complex, because it builds on a fragmented policy framework and there is no common EU forest policy (Wolfslehner et al. 2016). The Nordic bioeconomy program is rapidly developing and aims to combine environmental, social, and economic ambitions for an even more sustainable development in the Nordic region (Points 2018). In Eastern Europe, there is a lack of national bioeconomy strategies and action plans for the sustainable and circular use of the bioresources (Paşnicu et al. 2019; Vasary 2019).

French forests contain an important wood resource and cover more than 16 million ha. They are mostly mixed deciduous broad-leaved forests and are mainly private, with more than three million forest landowners. Coppice-with-standards (CWS) is a traditional management system developed over past centuries in Western and Northern Europe to ensure a continuous flow of a wide range of forest products (Buckley 1992). However, since the beginning of the twentieth century, CWS stands have progressively been converted to high forests (Huffel 1909), though they still frequently occur throughout France (5 million hectares, about 30% of the total productive forest area (IGN 2015)).

Today, the desire to develop renewable energy sources and supply wood chips to collective biomass boilers and power plants has created an increasing interest in the extraction of all forms of forest biomass. Different methods of logging are used in Europe; their selection depends on site conditions, silvicultural treatments, species composition, tree sizes, stand density, and the economic condition of each country. According to Asikainen et al. (2009), the proportion of mechanization varies greatly among European countries: the percentage is close to 100% in the Nordic countries, UK and Ireland, and notably smaller in Eastern Europe. The mechanization and whole-tree harvesting (WTH) make harvesting poor-quality wood as bioenergy profitable for the landowner (Adebayo et al. 2007; Spinelli and Magagnotti 2010). However, additional harvesting, in particular the extraction of fine wood [diameter < 7 cm], has come under debate. Indeed, despite the relatively small proportion of biomass in fine wood, it contains large amounts of nutrients (Weetman and Webber 1972; Triska and Cromack 1980; Augusto et al. 2015) and its removal could compromise forest productivity. Several studies have shown that removing fine wood has negative effects on long-term forest yield by reducing stand productivity over time; tree growth can decrease by 3 to 20% (Kimmins 1976; Grigal 2000; Nord-Larsen 2002; Peng et al. 2002; Thiffault et al. 2011; Wall 2012; Kaarakka et al. 2014; Miettinen et al. 2014; Achat et al. 2015; Egnell 2017). In this regard, the French recommendations for sustainable biomass harvesting have continuously been updated thanks to several scientific studies and increasing technical expertise (Cacot et al. 2006; Landmann and Nivet 2014). The latest recommendations take into account local conditions, in particular soil sensitivity to mineral exports (Landmann et al. 2018). It is highly recommended to leave at least 10% of the fine wood on the ground for non-sensitive soils and to increase this value to 30% on moderately sensitive soils. In the case of highly sensitive or poor soils, harvesting fine wood is not recommended; all fine wood should be left on the forest floor.

Forest management is a complex process, which requires both patience and acceptance of risk, and which includes environmental, economic, and social criteria. Not only is knowledge of the effects of nutrient losses due to WTH essential to maintaining forest soil fertility, economic issues are also crucial to guarantee forest sustainability. The emergence of new industries and new wood-derived products implies changes in silvicultural practices and forest management; these changes undoubtedly involve environmental risks but also long-term economic uncertainties for the future. Additional harvests will undoubtedly increase the profitability of the stand but the effects of more harvesting on the forest have not been sufficiently analyzed from an economic point of view. Furthermore, the increases in tree mortality have been highlighted in different forests around the globe (Van Mantgem et al. 2009; Peng et al. 2011; Westerling et al. 2006; Williams et al. 2013). A number of studies (Sáenz-Romero et al. 2017; Taccoen et al. 2019; Brandl et al. 2020) suggest that mortality rates will keep on increasing, while species that have not been impacted to date might be impacted in the future.

Forest investment is staggered over time; the return may occur decades after the initial investment. It is therefore necessary to compare cash flows occurring at different times. Faustmann (1849) considers a forest as a financial asset managed over an infinite horizon; he proposed a simple deterministic model to evaluate the land expectation value (LEV) over an infinite sequence of rotations. Discounting to determine the present value of future cash flows is therefore fully justified in forest economics (Samuelson 1976; Peyron and Maheut 1999; Terreaux 2008; Hanewinkel 2009; Hyde 2012). On this issue, Price (2014) and Brazee (2018) demonstrated the implications of various discount rates on net present values and showed how much time is crucial in many aspects of forest economics. In addition, silvicultural costs have an important effect on the net present value since these "front-end costs" emerge at the beginning of a rotation (Sauter and Mußhoff 2018). Timber prices also depend on wood quality (Cavaignac et al. 2005), variation in supply and demand (Caurla et al. 2010), and climatic policies (Buongiorno et al. 2011; Hanewinkel et al. 2013). More generally, forest investments can be subject to natural hazards (growth fluctuations, storms, diseases, fires, etc.) and economic risks (variations in inflation, supply and demand, wood prices and silvicultural costs, etc.), not to mention other political and social risks (Kant and Alavalapati 2014; Terreaux and Chavet 2016).

The main objective of this study was to compare the land expectation value (LEV) for even-aged oak (*Quercus petraea* (Matt.) Liebl.) and chestnut coppice (*Castanea sativa* Mill.) with oak standards under different wood prices and discount rates scenarios. Using current prices and silvicultural costs, we generated a series of cash flows and transformed these into Faustmann's LEV, assuming that future costs, prices, and stand growth were known. Nevertheless, tree survival is frequently hypothesized to be climate sensitive (Peng et al. 2011; Williams et al. 2013). With projections of increasing temperatures (O'Neill et al. 2017), drought frequencies, and intensities, a number of studies suggest that mortality rates will keep on increasing (e.g., Neumann et al. 2017; Sáenz-Romero et al. 2017).

The LEV was assessed according to two harvesting scenarios: (1) whole-tree harvesting and (2) conventional harvesting (all fine wood is left on site). Whole-tree harvesting scenario was then analyzed under the assumption of decline in long-term productivity due to intensive biomass removal and nutrient exports by fine wood. We therefore explored the economic consequences on LEV by simulating 10 scenarios of decrease in tree growth in both height and diameter from 1 to 10%. This study also aimed to find possible trade-offs between the short-term economic gain and the long-term decline in productivity.

2 Material and methods

2.1 Harvesting scenarios and working hypotheses

We simulated two plausible scenarios each for even-aged oak stand and CWS: (1) whole-tree harvesting (WTH), and (2) conventional harvesting (CH) without any export of fine wood. Three categories of potential wood uses were defined according to dimensional characteristics: (i) large wood [diameter > 22 cm] for timber, (ii) medium wood [7–22 cm] for industrial wood or fuelwood, and (iii) fine wood [diameter < 7 cm] only for fuelwood. In WTH scenario, all the fine wood was harvested at each silvicultural operation, with the assumption that 10% of the fine wood would systematically be left on the forest floor due to harvesting losses (Landmann et al. 2018). In this case, the decline in stand productivity was assumed to affect tree growth, in height and diameter, from 1 to 10% due to additional nutrient exports (Nord-Larsen 2002; Wall 2012; Achat et al. 2015). In CH scenario, large wood was sold as timber and only medium wood was harvested for energy and other industrial uses. All the fine wood was left on the ground. We assumed here that soil fertility and stand productivity would not be affected because the high nutrient content of fine wood would ensure the maintenance of soil fertility (Lattimore et al. 2009; Landmann and Nivet 2014).

Silvicultural operations in each scenario were triggered at the same reference basal area; this postponed thinning operations and coppice harvesting date from 1 to 5 years depending on the decrease in height and diameter as well as the stand type.

2.2 Growth models and volume equations

We modeled two plausible stands on medium-fertility sites (Jarret 2004; Bedeneau 1988): (i) pure even-aged sessile oak stand and (ii) chestnut coppice with oak standards stand (CWS). We then used the dendrometric outputs (Bessaad et al. 2020) to compute subsequent volumes through tree allometric equations, thereby ensuring consistency in our estimates by compartment (stem, crown, branches) and by cutting level. The harvested volume, at any given date of silvicultural operation, is one of the most important pieces of information for conducting economic analyses. This method allowed us to compute, for both stands, the profitability of each scenario (WTH and CH) using Microsoft Excel software.

2.2.1 Pure even-aged sessile oak

The "Fagacées" model developed by Le Moguédec and Dhôte (2012) allowed us to obtain the necessary dendrometric data (Table 1). We opted for the recommended silvicultural pathway of sessile oak on a medium-fertility site class (site fertility index: H_{100} = 27.5 m) from Jarret (2004) because of using average economic data afterwards. We then reproduced, as closely as possible, the silvicultural pathway on the basis of the relative density index (RDI) value (Reineke 1933), which is the ratio of the actual number of stems (N) in a stand and the theoretical number of stems ($N_{\max}$), this stand could support with the same diameter at breast height (DBH) (Eq. 1).

$$RDI = \frac{N}{N_{max}} \tag{1}$$

Table 1 Output parameters for even-aged sessile oak

Age	G (m^2. ha^{-1})	N	g (m^2)	D (cm)	H (m)	N_{max}	RDI
15	4.4	3447	0.00	4.0	5.7	16305	0.22
24	9.2	1907	0.00	7.8	9.3	5237	0.37
36	12.7	1155	0.01	11.8	13.2	2668	0.42
42	14.0	718	0.02	15.8	15.6	1757	0.46
51	15.4	585	0.03	18.3	18.0	1246	0.48
60	16.6	464	0.04	21.3	20.2	936	0.50
70	17.8	333	0.05	26.0	22.4	731	0.50
78	19.3	297	0.06	28.7	23.9	568	0.53
87	19.0	225	0.08	32.8	25.4	457	0.54
99	22.8	211	0.11	37.0	27.3	379	0.56
108	23.0	174	0.13	41.0	28.6	317	0.55
117	22.6	141	0.16	45.1	29.9	270	0.55
129	23.2	116	0.20	50.5	31.5	232	0.55
138	24.3	106	0.23	54.0	32.7	201	0.55
147	24.4	93	0.26	57.8	33.9	175	0.54
159	25.7	83	0.31	62.8	35.4	152	0.54
168	24.7	70	0.35	67.0	36.6	122	0.53
180	26.8	65	0.41	72.5	38.2	115	0.56
195	32.1	65	0.49	79.3	40.1	101	0.64
210	37.5	65	0.58	85.7	42.1	88	0.74

G, basal area of the stand; *N*, number of trees per hectare in the stand; *g*, basal area of the tree; *D*, tree diameter; *H*, tree height; N_{max}, theoretical maximum number of trees obtained from the self-thinning equation; *RDI*, relative density index

2.2.2 Coppice-with-standards

We assumed here that the coppice and the standards covered equal parts of the area (Bary-Lenger and Nebout 1993) and that tree growth for the coppice and the standards was unrelated. We separately simulated the part of chestnut coppice and oak standards using growth models and biomass equations. We modeled oak standards using "Fagacées" and used Bedeneau (1988) general logistic model for chestnut coppice, thus allowing us to plot the evolution curves in biomass (Eq. 2) and height (Eq. 3) according to age.

$$Biomass\ (t.ha^{-1}) = 124 \times \left(1 - e^{(-0.078 \times age)}\right)^{1.4} \tag{2}$$

$$Height\ (m) = 17.9 \times \left(1 - e^{(-0.049 \times age)}\right)^{0.67} \tag{3}$$

We then estimated tree circumference at breast height (C_{130}) for chestnut coppice from real observations (n =504) and measurements of tree total height from 2 to 24 m and tree circumference from 2 to 102 cm on four sites in the Centre-Val de Loire region (Appendix Fig. 7). C_{130} depends on the total height (H_{tot}) and varies according to the following simple linear regression model (R^2 =99.05; P <0.05) (Eq. 4).

$$C_{130} = (0.836321 + 0.350799 \times H_{\text{tot}})^2 \tag{4}$$

All dendrometric parameters for CWS stand are presented in Table 2.

2.2.3 Volume equations

We used tree allometric equations resulting from the EMERGE project (Deleuze et al. 2014b; Deleuze et al. 2014a) to compute woody biomass production by cutting level (Eqs. 5 to 9). We used cutoff height (H_{cut}) as the main parameter to distribute volumes between the stem and the crown. This parameter is defined by the French National Forest Inventory (IFN, now IGN) as the height of the stem measured approximately at the first major fork in the trunk, or, where

Table 2 Output parameters for chestnut coppice and oak standards

Age	G (m^2. ha^{-1})	N		g (m^2)		D (cm)		H (m)	
		Oak	Chestnut	Oak	Chestnut	Oak	Chestnut	Oak	Chestnut
15	8.8	1508	1516	0.00	0.00	4.0	7.6	5.7	11.6
30	17.7	750	1067	0.01	0.01	10.0	11.9	11.4	15.0
60	18.5	189	1067	0.04	0.01	21.3	11.9	20.2	15.0
90	21.1	102	1067	0.09	0.01	34.0	11.9	25.9	15.0
120	16.8	30	1067	0.17	0.01	46.1	11.9	30.3	15.0
150	20.0	30	1067	0.27	0.01	59.1	11.9	34.3	15.0
180	24.2	30	1067	0.41	0.01	72.5	11.9	38.2	15.0
210	29.1	30	1067	0.58	0.01	85.7	11.9	42.1	15.0

G, basal area of the stand; *N*, number of trees per hectare in the stand; *g*, basal area of the tree; *D*, tree diameter; *H*, tree height

appropriate, the height at which a more than 10% decrease in diameter is reached. Indeed, this parameter is very informative of the shape of the tree and has been systematically integrated into inventories since 2006. We deduced a relationship between H_{tot} and H_{cut} from dendrometric surveys carried out at the nine sites. The average value of $\frac{H_{cut}}{}$ H_{tot} for each species was 0.41 ± 0.1; C_V = 25% (n = 41) for sessile oak and 0.50 ± 0.07; C_V= 13.38% (n = 504) for chestnut.

Volumes were calculated in three steps, where "a, b, c, d, e, f, g, α, and β" are the parameters specific to each species but without units (Appendix Table 5).

First, we calculated total tree volume (V_{tot}) as follows (Eq. 5).

$$V_{tot}\ \left(m^3\right) = \frac{H_{tot}.C_{130}{}^2}{4\pi\left(1-\frac{1.30}{H_{tot}}\right)^2} \times \left(a + b\frac{\sqrt{C_{130}}}{H_{tot}} + c\frac{H_{tot}}{C_{130}}\right) \quad (5)$$

Second, the total volume was distributed by compartment (stem (V_{stem}) and crown (V_{crown})) according to the following Eqs. (6) and (7):

$$V_{stem}\ \left(m^3\right) = V_{tot}\left(d + e.ln\left(\frac{H_{cut}}{H_{tot}-H_{cut}}\right) + f\frac{\sqrt{C_{130}}}{H_{tot}} + \frac{g}{C_{130}}\right) \quad (6)$$

$$V_{Crown}\left(m^3\right) = V_{tot}-V_{stem} \quad (7)$$

Third, we used Eqs. (8) and (9) to obtain stem volume up to the cutting level (V_{stem_cut}) and crown volume (V_{crown_cut}), respectively:

$$V_{stem\_cut}\ \left(m^3\right) = V_{stem} \times \left(1-\frac{C_{cut}^3}{C_{130}^3}\left(1-\frac{1.30}{H_{tot}}\right)^3\right) \quad (8)$$

$$V_{Crown\_cut}\left(m^3\right) = V_{Crown} \times \left(1-\left(\frac{C_{cut}}{C_{130}}\left(1-\frac{1.30}{H_{tot}}\right)\left(\frac{3-\beta}{3\alpha}\ crown\ part\right)^{-\frac{1}{3}}\right)^{3-\beta}\right) \quad (9)$$

2.2.4 Potential effects of climate change on tree mortality

Tree mortality is becoming increasingly important in the discussion of how to adapt forests to climate change, to preserve their ecosystem services, and to mitigate the risk of induced economic losses. The Fagacées model used in our study for oak has not been calibrated on very young stands (Le Moguédec and Dhôte 2012). The trees growth, involving self-thinning, was the only cause of mortality. For CWS, chestnut mortality is given in the (Appendix Fig. 8). The current mean annual mortality rate is 0.50% per year in Europe's forests, ranging from 0.31 per year in central-western Europe to 1.39% per year in south-western Europe.

For our analysis, we defined two scenarios of a potential increase in annual tree mortality due to drought and temperature increment in forest. First, we assumed a gradual increase in tree mortality from 0.1 to 1.3% over the stand rotation. Second, we modeled tree growth under constant mortality rates over time from 0.1 to 1%.

2.3 Economic parameters

We calculated the LEV (Eq. 10) under different harvesting scenarios while respecting Faustmann's (1849) main assumptions, an environment in which prices, costs, and technology are constant.

$$LEV\ (€) = \sum_{i=0}^{t}\frac{R_i-C_i}{(1+r)^i} \times \frac{(1+r)^t}{(1+r)^t-1} \quad (10)$$

R_i is the revenue received at time i; C_i is the cost incurred at time i; and r is the discounting rate over time i.

We transformed the silvicultural pathway schedule (Appendix Tables 6 and 7) into costs and revenue over the

Table 3 Average silvicultural costs for sessile oak in north-central France (Saint-André et al. 2019)

Task description	Average cost (€ ha^{-1})
Soil preparation and regeneration cost	788
Mechanical cleaning	666
Manual cleaning	1353
Creation of racks	136
Racks maintenance	97
Maintenance of objective trees marking	82
Thinning costs: paint making	120

entire rotation of each stand. Occasional costs were estimated based on averages for each type of silvicultural operation (Table 3) (Saint-André et al. 2019; Bessaad et al. 2020). Occasional revenue is only related to the timber and fuelwood sales that follow the cutting schedule for each stand. We then calculated the fixed annual revenue and charges (management fees at 15 € ha^{-1}, insurance costs and taxation at 15 € ha^{-1}, other annual income such as hunting at 30 € ha^{-1}), based on expert evaluation. We did not take into account possible financial aid for afforestation, improvement of existing stands, equipment, or management because the application of these schemes remains marginal.

Concerning wood product prices, we first drew the price curve for sessile oak timber, based on regional sales data for private forests in 2017. The average timber price for standard quality followed the relation: P = 48.66 (Vol) + 61.67 and depended on mean tree volume (Vol). The average price for fuelwood was 12.6 € m^{-3}, and ranged from 5 to 20 € m^{-3} depending on species, tree size, forest location, and skidding distance. We examined the LEV for both types of stands assuming a decrease in tree growth both in height and diameter caused by fine wood removal.

To better understand the effects of our main variables, we conducted a sensitivity analysis based on price variations observed over the last few decades. Timber prices varied from −50 to +50%, whereas fuelwood prices showed a wider range, from −50% to +150%, compared to the average value of 12.6 € m^{-3} obtained for 2017. Choosing the discount rate is crucial to our research because of the long-term nature of the impacts of WTH on soil fertility. We used a rate r of 3% to discount both costs and profits of various natures at different times. We then conducted a sensitivity analysis for the discount rate covered a range of 2–4%, which seems to be adequate for European forestry (Lebègue et al. 2005; Benítez et al. 2007; Terreaux 2008; Terreaux 2018).

3 Results

3.1 Comparison of CWS and even-aged oak LEV

We first estimated the global profitability for even-aged oak and CWS according to the same scenario (WTH) by maximizing the LEV (r = 3%) using as command variable the rotation age. The graphs in (Fig. 1) show that bare land value ranged from 957 for CWS to 1292 € ha^{-1} for even-aged oak. The mathematically optimum rotation age for both silvicultural systems was 177 years, but the curve for CWS tends to reach the optimum earlier than does the curve for even-aged oak. In the case of an early harvest, for example, at the age of 120 years, the loss in LEV was less pronounced in CWS (10%) than in even-aged oak stand (25%). Therefore, the CWS system provides the owners or managers forest with more flexibility, making it possible to cut before the calculated optimal date to take advantage of good market conditions, for example. The LEV of even-aged oak was higher because this type of stand produces more large wood (Fig. 2), in particular at the final cutting: 437 m^3 ha^{-1} compared to 187 m^3 ha^{-1} for CWS. The larger the diameter of oak timber, the higher its value. Fine and medium wood yield from the CWS was 1079 m^3 ha^{-1} (including 590 m^3 ha^{-1} produced by the chestnut coppice), and it was much higher than in even-aged oak stand (722 m^3 ha^{-1}) during the same rotation.

3.2 Harvesting fine wood under the assumption of a decrease in tree growth during subsequent rotations

Our results (Fig. 3) showed that WTH improved global profitability compared to CH scenario by 36% for even-aged stand and 64% for CWS. This gain was higher for the CWS regime due to the high ratio of fine wood

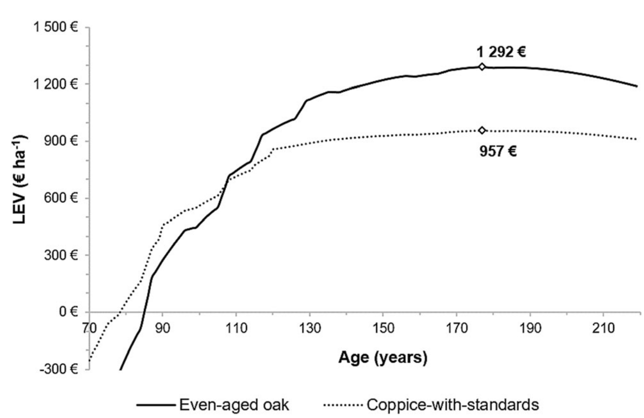

Fig. 1 Changes in LEV (€ ha^{-1}) in the whole-tree harvesting scenario for even-aged oak and coppice-with-standards with an optimal rotation age for both stands

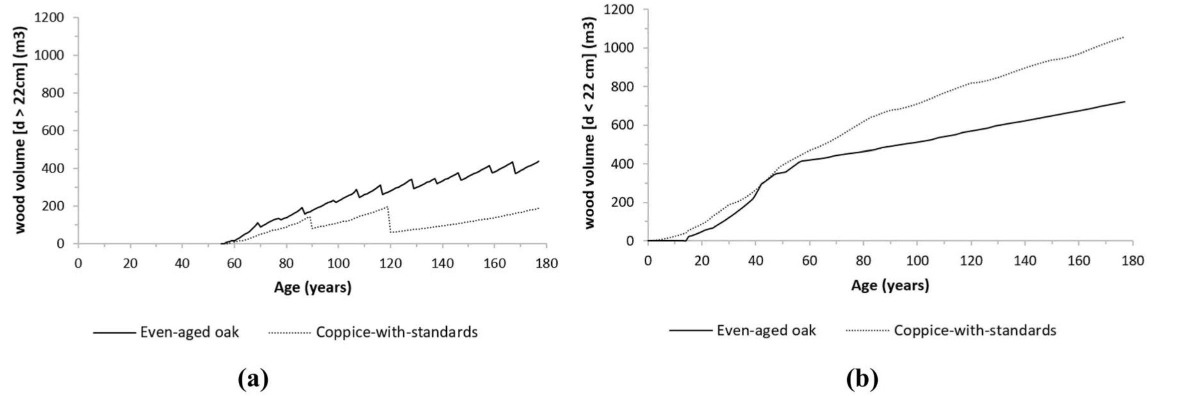

Fig. 2 Wood volumes. **a** Final large wood production, peaks, and troughs indicate thinnings. (**b**) Fine and medium wood production along the rotation

(20%) in the total fuelwood production (only 13% in even-aged stand). More specifically, the chestnut coppice contains a high proportion of fine wood (27% of its production). Moreover, leaving 30% of the fine wood on the ground improved profitability by 28% for even-aged oak and by 50% for CWS, which represents only slight losses in expected gain for WTH (8%) and even-aged oak (14%).

The simulations of WTH, under the assumption of a decrease in tree growth, allowed us to quantify the associated impact on profitability due to harvesting the fine wood. Our results showed that a decrease of 2.3% in tree growth for even-aged oak and 3.4% for CWS, based on the basal reference area, postponed thinning operations and consequently delayed revenue for up to 3 years for even-aged oak and 5 years for CWS. This decrease in tree growth led us to the same LEV as CH for both stands (Fig. 3). In even-aged stand, the total volume including fuelwood was reduced by 2.7% whereas timber production was reduced by 3.7%. For CWS, the loss in total production was more pronounced at 7.3%, while timber volume was reduced by 4.8%.

We also found an almost linear relation between the LEV and the tree growth (Fig. 3). The LEV was very close to zero for both stands if tree growth had been reduced by 9%. In this case, total production was reduced by 12.5% for even-aged oak stand and by 18.5% for CWS, while timber production was reduced by 15.3 and 12%, respectively.

3.3 Price sensitivity analysis

Fluctuating wood prices had a significant effect on LEV (Fig. 4). First, a near doubling (+93%) of the fuelwood price (24.32 € m^{-3}) allowed an equal LEV for both types of stands; beyond this price, CWS became the most profitable investment. Second, raising oak timber prices by 50% increased the difference between stand LEVs from 26 to 37% in favor of even-aged stand. Conversely, a drop of 25% in timber prices made CWS more profitable than even-aged stand, whereas a drop of 40% and below led to negative values. With a slight fall (10%) in timber prices and a simultaneous 50% rise in energy prices, the LEVs of both stands became equal. CWS became more

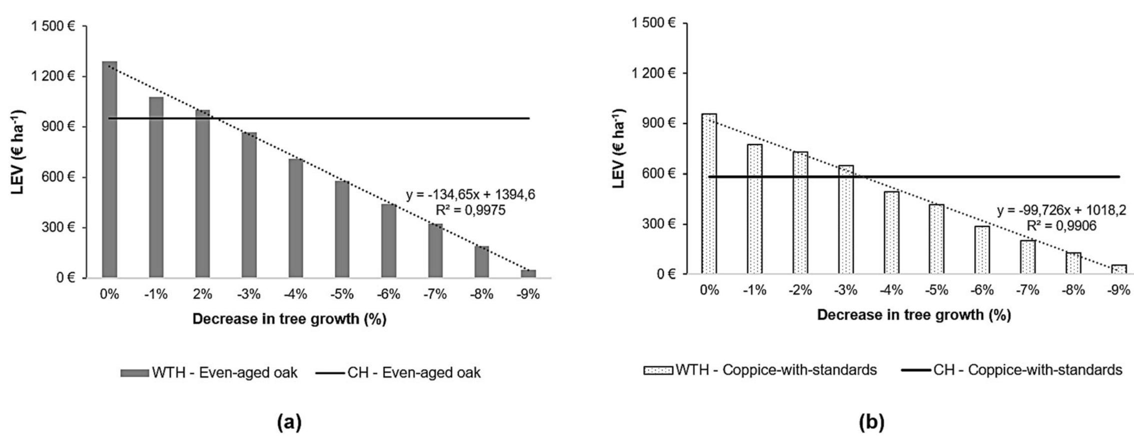

Fig. 3 Effects of a 1 to 9% decrease in tree growth on the LEV (€ ha^{-1}) in the whole-tree harvesting scenario compared to conventional harvest without any export of fine wood, for even-aged oak (**a**) and coppice-with-standards (**b**)

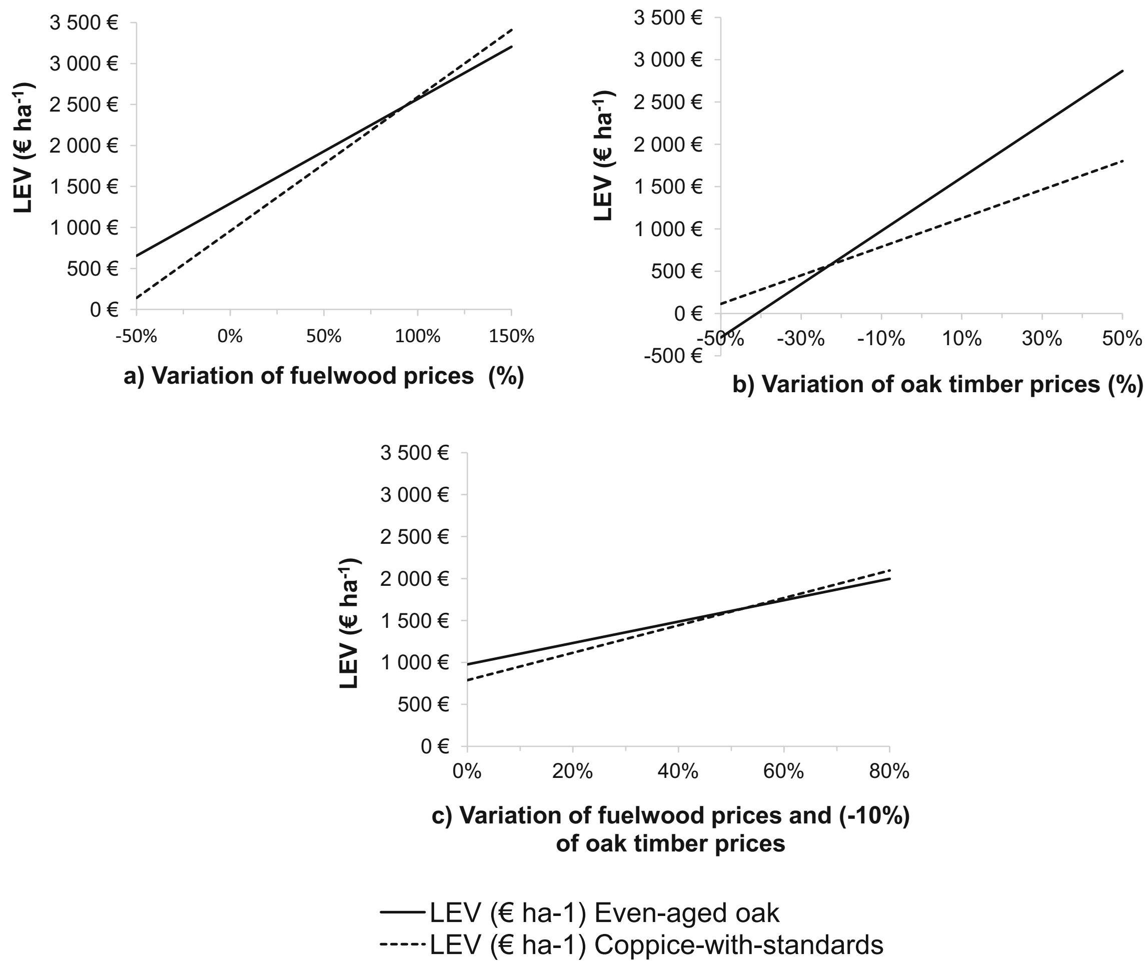

Fig. 4 Prices sensitivity analysis, effect of fuelwood and timber price variations on the LEV (€ ha^{-1}) of even-aged oak and coppice-with-standards: **a** fluctuating fuelwood prices (average = 12.6 € m^{-3}), from −50 to +150%, **b** fluctuating oak timber prices, from −50 to +50%, **c** rising fuelwood prices, up to +80% with a slight decrease in oak timber prices

advantageous when energy prices exceeded 20 € m^{-3}. It should be noted that the LEV was more sensitive to timber price fluctuations than to fuelwood prices in even-aged stand because of the high economic value of timber and its large part in the total discounted wood revenue (Fig. 5). At rotation end, the proportion of timber in the discounted wood revenue for even-aged oak was 71%, with only 29% for fuelwood including 8% for fine wood. For CWS, fuelwood provided about half (49%) of the discounted wood revenue including 5 and 7% of oak and chestnut fine wood, respectively.

3.4 Impact of discount rate *r* on the LEV

For both stands, forest investment was generally more profitable under low discount rates (Fig. 6). However, for the very low discount rate of r = 2%, the optimal rotation age was not reached. The LEV was 10,500 € for even-aged oak and 6600 € for CWS at 220 years, our maximum simulation period. At medium discount rates, 2.5 and 3%, the LEV ranged from 4300 to 1290 € for even-aged oak and from 2777 to 957 € for CWS. The optimal rotation age was reached for both stands at 205 years (r = 2.5%) and 177 years (r = 3%). For r > 3%, the LEV was negative for both stands.

3.5 Consequences of increased tree mortality triggered by climate change

For both scenarios, the decrease in the LEV of even-aged oak was more significant than CWS (Table 4). First, the gradual increases in annual tree mortality over time reduced the LEV in even-aged oak by 90 ± 1 € ha^{-1} for every 0.1% and 47 ± 4 € ha^{-1} for CWS. A gradual increase in tree mortality of 0.6% along even-aged oak rotation reduced the LEV of even-aged oak by almost 50%, while at 0.9%, the LEV was reduced by 70%. For CWS, the LEV was reduced by half at 0.9% and by 70% at 1.2%.

Second, constant mortality rates had more negative effect on the LEV than gradual increases. Both LEVs

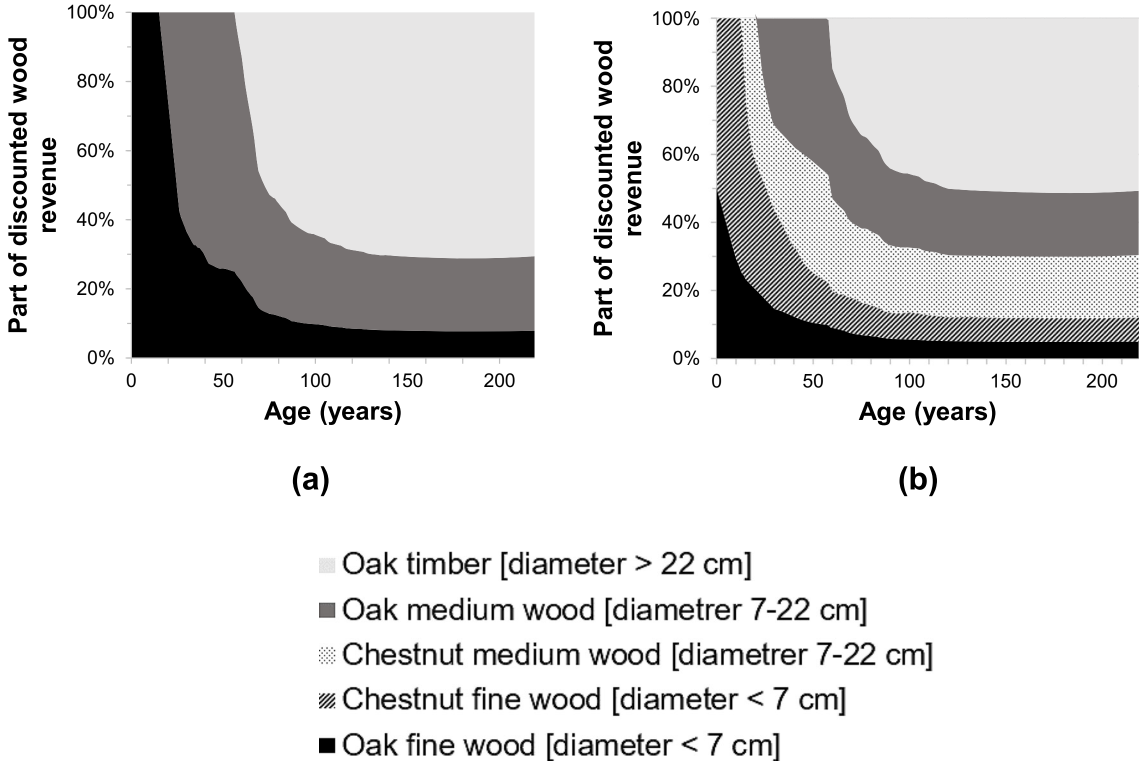

Fig. 5 Changes in the proportion of discounted wood revenue by species, diameter class, and wood use for even-aged oak (**a**) and CWS (**b**). The filled area represents sessile oak and the hatched area represents chestnut coppice

were reduced by half at 0.4–0.5%. When increases in annual mortality rates passed 0.6%, the LEVs were reduced by more than 70%.

4 Discussion

4.1 Potential trends in forest productivity and economic value

A forest's economic value depends mostly on the volume, dimensions, and quality of the wood that it can produce,

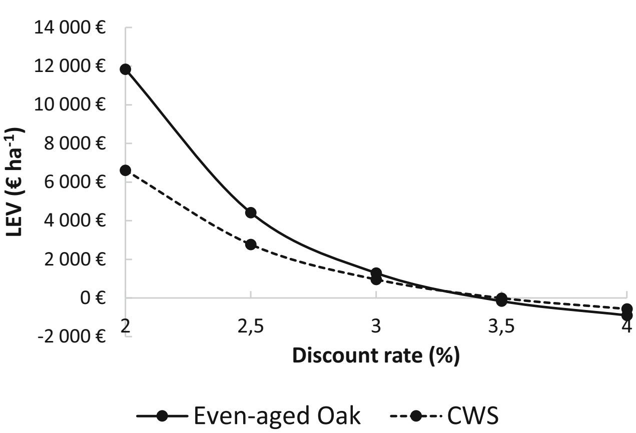

Fig. 6 Sensibility analysis of the consequences of using different discount rates ($r = 2$; 2.5; 3; 3.5; and 4) on the LEV

thus on its soil fertility, and not only on wood prices and silvicultural costs. The volumes we obtained were very close to other previous studies: large wood volume including thinning operations was 922 m^3 ha^{-1} in even-aged oak stand and 415 m^3 ha^{-1} for CWS stand at the age of 177 years. For the same age and site fertility index, Jarret (2004) estimated total volume in an even-aged oak stand at 859 m^3 ha^{-1}. For CWS stand, Bary-Lenger and Nebout (1993) revealed that oak timber yield ranged from 1.81 to 3.05 m^3 ha^{-1} per year for standards, which provides between 380 and 540 m^3 of timber at the end of the rotation.

Our chestnut coppice on medium-fertility soil produced 108 m^3 ha^{-1} at every cutting. This is consistent with Venanzi et al. (2016), who estimated 175.3 m^3 ha^{-1} through a study carried out on a chestnut CWS in the mountains of central Italy on high fertility sites with a very high yield. Their estimates are very high, closer to the production of a simple coppice regime (Bedeneau 1988; Bourgeois et al. 2004). In addition, the number of standards in CWS system has an effect of the LEV because they provide more timber. Poor stand in standards has less economic value than our simulated stand with equal proportions of coppice and standards. However, the LEV remains the highest in even-aged oak whatever the proportions of coppice and standards in CWS system because oak trees cover 100% of the area and produce more high timber value than in CWS.

Table 4 Consequences of gradual and constant increase in annual mortality rate (%) on the LEV (€ ha^{-1})

	Annual mortality increases (%)	Average survival rate (%)	LEV (€ ha^{-1}) Even-aged oak	LEV (€ ha^{-1}) CWS
Gradual increases in tree mortality (%)	0.1–0.2	76.97	1034	789
	0.1–0.3	71.26	942	737
	0.1–0.4	66.48	851	686
	0.1–0.5	62.48	760	636
	0.1–0.6	59.12	668	587
	0.1–0.7	56.31	577	540
	0.1–0.8	53.95	485	493
	0.1–0.9	51.98	394	448
	0.1–1.0	50.33	302	403
	0.1–1.1	48.94	211	360
	0.1–1.2	47.79	120	317
	0.1–1.3	46.82	28	276
Constant mortality rate (%)	0.1	83.77	1125	843
	0.2	70.16	958	732
	0.3	58.75	781	624
	0.4	49.19	625	520
	0.5	41.18	459	420
	0.6	34.47	292	323
	0.7	28.84	126	228
	0.8	24.13	-41	137
	0.9	20.19	-207	49
	1.0	16.88	-374	-36

It should also be noted that the results obtained from this study concern average fertility sites. Other soil fertility indexes were not investigated because of the lack of data on CWS management as well as specific silvicultural costs to each fertility class. We therefore focused on comparison between the two harvesting scenarios for both management systems on sites with medium fertility.

For WTH scenarios, our results showed that bare land value ranged from 957 to 1292 € ha^{-1} under a discount rate of 3%. The LEV was very sensitive to changes in discount rates; the lower rates lead to extend the final harvest age and increase standing volume but this will lead to greater environmental degradation in future (Pukkala 2016).

The even-aged management system has been the reference silvicultural treatment since the beginning of the twentieth century owing to its high production of timber and high prices, and it has been opposed to CWS forests (see, in particular, Lorentz and Huffel (1929) and Lanier et al. (1986)). Indeed, in the current context of low fuelwood prices, the even-aged system remains more profitable than CWS because of the high timber prices compared to fuelwood. Nonetheless, in light of the EU's renewable energy targets, biomass will become the most important source of renewable energy, and fuelwood prices could increase in the future geopolitical context. We showed that an increase of 50% in fuelwood prices associated to 10% decrease in timber prices aligned the profitability of the two types of stands. CWS could therefore once again become an attractive regime, producing both timber and fuelwood, and may be one of the most efficient systems for the future.

4.2 Is whole-tree harvesting profitable over the long term?

The environmental effects of increasing harvesting pressure on forests are still not fully understood. Moreover, not only the ecological aspects and potential losses in productivity but also the related economic concerns in order to find more possible trade-offs should be taken into account. Fine wood represents a non-negligible part of global forest profitability regardless of the type of stand. WTH improved the profitability of even-aged stand by 36% of CWS by 64% due to the additional harvest of fine wood, which amounts to 13 and 20% of the total fuelwood volume, respectively. Furthermore, leaving 30% of the fine wood behind after each harvesting operation, as recommended by Landmann et al.

(2018), did not much affect the expected gain: losses were relatively slight in even-aged oak (8%) and in CWS (14%). We would therefore fully endorse this recommendation, if leaving 30% of the fine wood meant there would be no detrimental effect on tree growth and forest productivity.

A decrease in annual tree growth of only 2.3% for even-aged oak and 3.4% for CWS had a large impact on forest profitability and was enough to bring the LEV back to the same level as the CH scenario. It is therefore inadvisable to harvest fine wood beyond these growth decrease percentages. Moreover, a 9% decrease in tree growth led to near-zero LEVs for both stands, due to total wood production reduced by 12.5% in even-aged oak stand and 18.5% in CWS. More specifically, the decline in profitability for even-aged stand was primarily due to reduced timber production (−15.3%), compared to −9% for fuelwood. Conversely, the decline in profitability for CWS was mostly due to reduced fuelwood production (−21%), compared to −11.8% for timber. For lower fertility sites with a very low LEV, the silvicultural pathway should be adapted in order to maintain the economic value of the forest.

Our economic analysis is in line with previous research on the environmental impacts of WTH, which showed that harvesting fine wood reduced tree growth in subsequent rotations by 3 to 20% (Kimmins 1976; Grigal 2000; Nord-Larsen 2002; Peng et al. 2002; Thiffault et al. 2011; Wall 2012; Kaarakka et al. 2014; Achat et al. 2015; Egnell 2017). The current guidelines for sustainable biomass harvesting (Landmann et al. 2018) recommend leaving 10 to 30% of the total fine wood volume on the ground and not exporting any fine wood in case of poor or sensitive soils. Our study supports these recommendations: a small proportion, though not all, of the fine wood should be left in the forest. Leaving all of the fine wood on the forest floor does indeed affect forest profitability. We showed that the proportion of fine wood in total wood revenue was higher at the beginning than at the end of the rotation; it declined gradually to reach 8% of the discounted wood revenue at 120 years for even-aged stand and 12 at 140 years for CWS. Therefore, harvesting fine wood does not add the same value at all cutting cycles; the discounted profits depend on time preference and changes in the proportion of fine wood in the total harvest.

4.3 How do increases in tree mortality due to climate change affect the forest profitability?

Extreme events such as abnormal droughts or heatwaves are important drivers of tree mortality, and they are expected to increase in frequency and intensity with climate change (Peng et al. 2011; Taccoen et al. 2019). However, disentangling the effects of climate change on the temporal increase in tree mortality from those of management and forest dynamics remains a challenge. Besides climate variability, tree mortality is further influenced by tree size as well as other biotic factors (van Mantgem et al. 2009; Peng et al. 2011). Age is an important driver of tree mortality, with individual mortality probability decreasing with age over the first century of a tree life (Neumann et al. 2017). In addition, Sáenz-Romero et al. (2017) indicated a significant but moderate response of tree height to climate variation on oak population at a reference age of 10 years.

Our analysis is limited due to the multitude of factors controlling tree mortality, but the use of early warning could highlight some economic concerns of the future. Our results show, for both mortality scenarios, that economic losses due to the potential increases in tree mortality triggered by climate change might be very significant. Consequences of widespread tree mortality would seriously affect the forest profitability and compromise long-term economic returns, especially wood revenues. Changes in silvicultural and harvesting practices should therefore be further explored in order to adapt forests to future climatic variations. Moreover, a combined effect of increased tree mortality and decrease in tree growth due to intensive harvesting may have a large impact on all ecosystem services, including wood and non-wood products, carbon sequestration, and air and water quality.

5 Conclusion

Our study demonstrates that WTH makes the forest more profitable as long as the impact on tree growth remains under 2.3% for even-aged oak stand and 3.4% for coppice-with-standards. This duality between environmental risk and economic gain requires trade-offs to guarantee forest sustainability. Indeed, our findings support the current guidelines for sustainable biomass harvesting, which advocate for leaving a small proportion of fine wood on the forest floor. Decision makers need to agree on this trade-off and should remain sensitive to environmental and social dimensions while including economic analyses in their decisions. For a better understanding of economic vulnerability of forests, tree mortality derived by climate variation should also receive major attention in order to maintain all ecosystem services.

Our work contributes to the question of forest economic sustainability, though certain aspects, such as risks and uncertainties, need to be further addressed.

Appendix

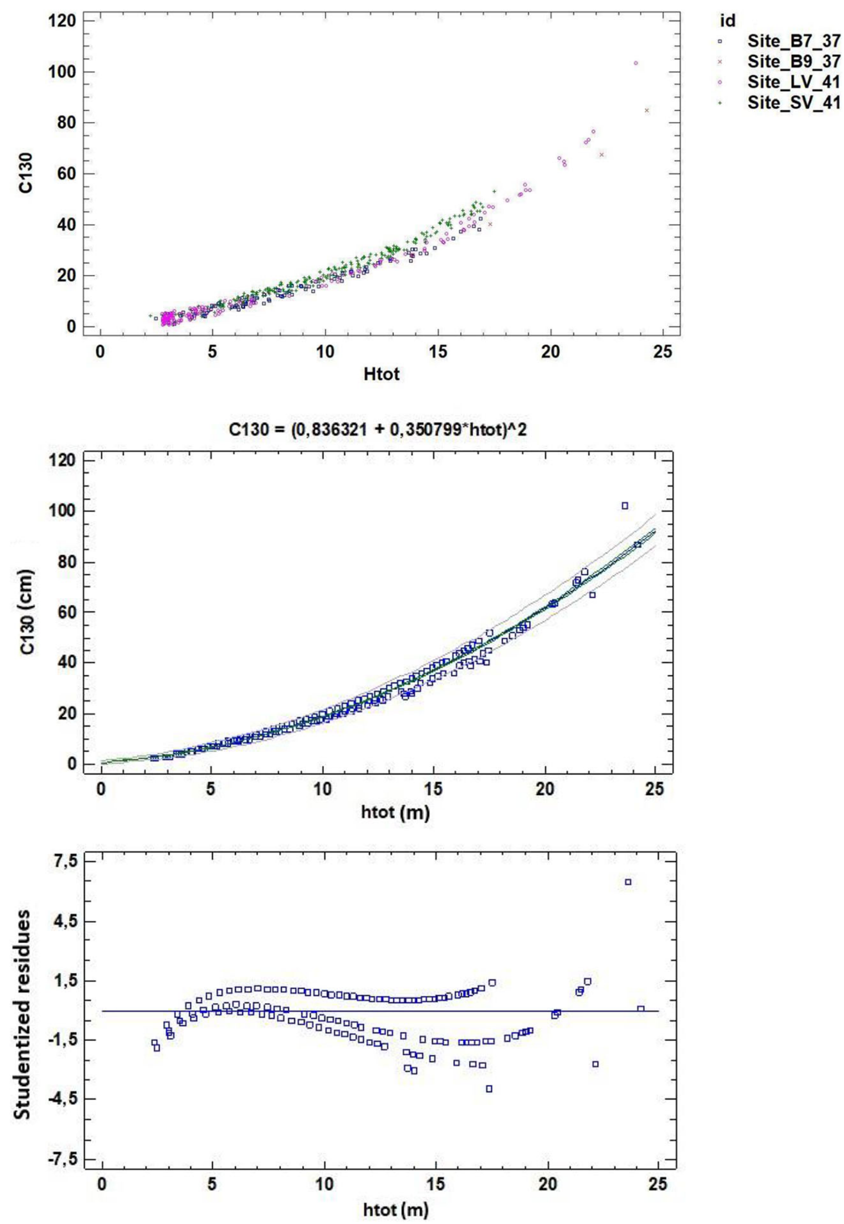

Fig. 7 Linear regression model for chestnut circumference C_{130} estimation

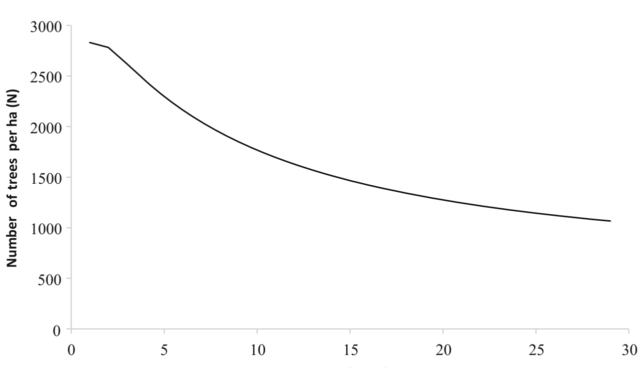

Fig. 8 Tree mortality along chestnut coppice rotation

Table 5 Specific parameters of volume equations from Deleuze et al. (2014b) and Deleuze et al. (2014a)

Parameters	Sessile oak	Chestnut
a	0.561	0.522
b	0.661	0.661
c	−0.002	−0.002
d	0.898	0.662
e	0.067	0.103
f	−4.059	−2.541
g	0.025	0.082
α	0.200	0.200
β	2.410	2.410

Table 6 Silvicultural pathway for even-aged sessile oak Jarret (2004)

Age	Silvicultural operations
0	Soil preparation
4; 15	Mechanical cleaning
9	Creation of racks
12; 14; 15; 17; 30	Racks maintenance
24	Manual cleaning
42; 52; 61; 72	Maintenance of objective trees marking
36; 42; 51; 60; 70; 78; 87 99, 108, 117, 129, 138, 147, 159, 180.	Thinning operations

Table 7 Silvicultural pathway for coppice-with-standards Bary-Lenger and Nebout (1993) and Jarret (2004)

Age	Silvicultural operation
0	Soil preparation
4; 15	Mechanical cleaning
9	Creation of racks
12; 14; 15; 17; 30	Racks maintenance
24	Manuel cleaning
42; 52; 60; 72	Maintenance of objective trees marking
30; 60; 90; 120; 150; 180	Coppice harvesting and thinning operations

Acknowledgments The authors gratefully thank the staff of French National Forestry Office (ONF), Christine Deleuze and Jean-Pierre Renaud, for providing the volumes equations resulting from the project EMERGE, and Hanitra Rakotoarison for her assistance acquiring economic data. We also thank Isabelle Bilger for her support during the realization of this work and Vicki Moore for proofreading the English manuscript.

Funding This research was funded by the DEFIFORBOIS project "Development and sustainability of the forest-wood sector in the Centre region," PSDR 4 project Centre-Val de Loire Region, France. This study has also been carried out with financial support from the French National Research Agency (ANR) in the frame of the Investments for the future Programme, within the Cluster of Excellence COTE (ANR-10-LABX-45) through the Project LUCAS.

Data availability The datasets generated and analyzed during the current study are available on OpenAIRE Zenodo: https://doi.org/10.5281/zenodo.4050092.

Declarations

Conflict of interest The authors declare no competing interests.

References

Achat DL, Deleuze C, Landmann G, Pousse N, Ranger J, Augusto L (2015) Quantifying consequences of removing harvesting residues on forest soils and tree growth - A meta-analysis. For Ecol Manag 348:124–141. https://doi.org/10.1016/j.foreco.2015.03.042

Adebayo AB, Han HS, Johnson L (2007) Productivity and cost of cut-to-length and whole-tree harvesting in a mixed-conifer stand. For Prod J 6:59

Alim'agri (2016) Programme national de la forêt et du bois 2016-2026. Ministère de l'Agriculture et de l'Alimentation, Paris. Available via DIALOG. agriculture.gouv.fr/telecharger/82112?token=599c7d066e840bf6459062cac7d3cc2b

Alim'agri (2017) Une Stratégie Bioéconomie Pour la France. Ministère de l'Agriculture et de l'Alimentation, Paris. Available via DIALOG. agriculture.gouv.fr/telecharger/83595?token=4b2095fafe14f075309cc193dda53d70. Accessed 17 Jan 2019

Asikainen A, Leskinen L, Pasanen K, Väätäinen K, Anttila P, Tahvanainen T (2009) The current state and the future of the forest machinery sector (in Finnish). Working Papers of the Finnish Forest Research Institute

Augusto L, Achat DL, Bakker MR, Bernier F, Bert D, Danjon F, Khlifa R, Meredieu C, Trichet P (2015) Biomass and nutrients in tree root systems-sustainable harvesting of an intensively managed *Pinus pinaster* (Ait.) planted forest. GCB Bioenergy 7:231–243. https://doi.org/10.1111/gcbb.12127

Bary-Lenger A, J-P Nebout (1993) Le chêne. Editions du Perron, Alleur-Liege, Belgium

Bedeneau M (1988) Croissance du taillis de châtaignier en France: premiers résultats. Ann Sci For 45:265–274. https://doi.org/10.1051/forest:19880307

Benítez PC, McCallum I, Obersteiner M, Yamagata Y (2007) Global potential for carbon sequestration: Geographical distribution, country risk and policy implications. Ecol Econ 60:572–583. https://doi.org/10.1016/j.ecolecon.2005.12.015

Bessaad A, Terreaux JP, Korboulewsky N (2020) Silvicultural and economic dataset for even-aged and coppice-with-standards managements in France. [Data set]. Zenodo. https://doi.org/10.5281/zenodo.4050092

Bourgeois C, Sevrin É, Lemaire J (2004) Le châtaignier: un arbre, un bois, 2e édition. Institut pour le développement forestier (IDF), Paris

Brandl S, Paul C, Knoke T, Falk W (2020) The influence of climate and management on survival probability for Germany's most important tree species. For Ecol Manag 458:117652. https://doi.org/10.1016/j.foreco.2019.117652

Brazee RJ (2018) Impacts of declining discount rates on optimal harvest age and land expectation values. J For Econ 31:27–38. https://doi.org/10.1016/j.jfe.2017.06.002

Buckley GP (1992) Ecology and Management of Coppice Woodlands. Chapman & Hall, London

Buongiorno J, Raunikar R, Zhu S (2011) Modélisation des conséquences possibles de la future demande bioénergétique mondiale pour le bois et les forêts en France. Rev For Fr 63:57–68. https://doi.org/10.4267/2042/43094

Cacot E, Eisner N, Charnet F, Léon P, Rantien C, Ranger J (2006) La récolte raisonnée des rémanents en forêt. Guide pratique. ADEME, Angers. Available via DIALOG. www.ademe.fr/sites/default/files/assets/documents/33691_remanents.pdf. Accessed 02 Nov 2017

Caurla S, Lecocq F, Delacote P, Barkaoui A (2010) The french forest sector model version 1.0. presentation and theoretical foundations. Cahier du LEF 2010-03. Laboratoire d'Economie Forestière, Nancy

Cavaignac S, Le Moguedec G, Préget R, Ibanez L (2005) Prix du bois de chêne et hétérogénéité des lots. Rev For Fr 57:431–442. https://doi.org/10.4267/2042/5063

Deleuze C, Morneau F, Renaud JP, Vivien Y, Rivoire M, Santenoise P, Hervé JC (2014a) Estimation harmonisée du volume de tige à différentes découpes. RDV Tech ONF 44:33–42
Deleuze C, Morneau F, Renaud JP, Vivien Y, Rivoire M, Santenoise P, Longuetaud F, Mothe F, Hervé JC, Vallet P (2014b) Estimer le volume total d'un arbre, quelles que soient l'essence, la taille, la sylviculture, la station. RDV techniques ONF 44:22–32
Egnell G (2017) A review of Nordic trials studying effects of biomass harvest intensity on subsequent forest production. For Ecol Manag 383:27–36. https://doi.org/10.1016/j.foreco.2016.09.019
European Commission (2018) Sustainable Bioeconomy for Europe: strengthening the connection between economy, society and the environment. Updated Bioeconomy Strategy, Belgium. Available via DIALOG. op.europa.eu/en/publication-detail/-/publication/edace3e3-e189-11e8-b690-01aa75ed71a1/language-en. Accessed 02 Mar 2019
Faustmann M (1849) Berechnung des Wertes, welchen Waldboden, sowie noch nicht haubare Holzbestande fur die Waldwirthschaft besitzen. Allg Forst Jagdztg 15:441–455
Grigal DF (2000) Effects of extensive forest management on soil productivity. For Ecol Manag 138:167–185. https://doi.org/10.1016/S0378-1127(00)00395-9
Hanewinkel M (2009) The role of economic models in forest management. CAB Rev: Perspect Agric Vet Sci Nutr Nat Resour 4:1–10. https://doi.org/10.1079/PAVSNNR20094031
Hanewinkel M, Cullmann DA, Schelhaas MJ, Nabuurs GJ, Zimmermann NE (2013) Climate change may cause severe loss in the economic value of European forest land. Nat Clim Chang 3:203–207. https://doi.org/10.1038/nclimate1687
Huffel G (1909) La conversion en futaie des forêts traitées en taillis sous futaie. Bull Soc For Franche-Comté et Belfort 10:238–247
Hyde WF (2012) The global economics of forestry. RFF Press, New York
IGN (2015) Indicateurs de gestion durable des forêts françaises métropolitaines. Institut national de l'information géographique et forestière (IGN), Paris inventaire-forestier.ign.fr/IMG/pdf/IGD_2015_FR.pdf
Jarret P (2004) Guide des sylvicultures—Chênaie atlantique. ONF/Lavoisier, Paris
Kaarakka L, Tamminen P, Saarsalmi A, Kukkola M, Helmisaari HS, Burton AJ (2014) Effects of repeated whole-tree harvesting on soil properties and tree growth in a Norway spruce (*Picea abies* (L.) Karst.) stand. For Ecol Manag 313:180–187. https://doi.org/10.1016/j.foreco.2013.11.009
Kant S, Alavalapati JRR (2014) Handbook of forest resource economics. Part 1: Fundamental topics in forest resource economics, Routledge, London
Kimmins JP (1976) Evaluation of the consequences for future tree productivity of the loss of nutrients in whole-tree harvesting. For Ecol Manag 1:169–183. https://doi.org/10.1016/0378-1127(76)90019-0
Landmann G, Augusto L, Pousse N, Gosselin M, Cacot E, Deleuze C, Bilger I, Amm A, Bilot N, Boulanger V, Leblanc M, Legout A, Pitocchi S, Renaud JP, Richter C, Saint-André L, Schrepfer L, Ulrich E (2018) Recommandations pour une récolte durable de biomasse forestière pour l'énergie - Focus sur les menus bois et les souches. GIP-ECOFOR, Paris & ADEME, Angers. Available via DIALOG. www.ademe.fr/sites/default/files/assets/documents/gerboise-guide-recommandations-2018.pdf. Accessed 23 Mar 2019
Landmann G, Nivet C (2014) Projet RESOBIO-Gestion des rémanents forestiers: préservation des sols et de la biodiversité. GIP-ECOFOR, Paris & ADEME, Angers. Available via DIALOG. www.ademe.fr/sites/default/files/assets/documents/resobio-2-rapport-final-2014mars.pdf. Accessed 02 Nov 2017
Lanier L, Badre M, Delabraze P, Dubourdieu J, Flammarion JP (1986) Précis de sylviculture. Ecole nationale du génie rural, des eaux et des forêts (ENGREF), Nancy
Lattimore B, Smith CT, Titus BD, Stupak I, Egnell G (2009) Environmental factors in woodfuel production: Opportunities, risks, and criteria and indicators for sustainable practices. Biomass Bioenergy 33:1321–1342. https://doi.org/10.1016/j.biombioe.2009.06.005
Le Moguédec G, Dhôte JF (2012) Fagacées: a tree-centered growth and yield model for sessile oak (*Quercus petraea* L.) and common beech (*Fagus sylvatica* L.). Ann For Sci 69:257–269. https://doi.org/10.1007/s13595-011-0157-0
Lebègue D, Baumstark L, Hirztman P (2005) Révision du taux d'actualisation des investissements publics. Commissariat Général au Plan (CGP), France
Lorentz B, Huffel G (1929) Les débuts de l'Enseignement forestier en France. Ecole nationale du génie rural, des eaux et des forêts (ENGREF), Nancy
Miettinen J, Ollikainen M, Nieminen TM, Ukonmaanaho L, Laurén A, Hynynen J, Lehtonen M, Valsta L (2014) Whole-tree harvesting with stump removal versus stem-only harvesting in peatlands when water quality, biodiversity conservation and climate change mitigation matter. For Policy Econ 47:25–35. https://doi.org/10.1016/j.forpol.2013.08.005
MTES (2018) Stratégie Nationale de Mobilisation de la Biomasse (SNMB). Ministère de la Transition Ecologique et Solidaire, Paris. Available via DIALOG. www.ecologique-solidaire.gouv.fr/sites/default/files/Strat%C3%A9gie%20Nationale%20de%20Mobilisation%20de%20la%20Biomasse.pdf. Accessed 6 Jan 2019
Neumann M, Mues V, Moreno A, Hasenauer H, Seidl R (2017) Climate variability drives recent tree mortality in Europe. Glob Chang Bio 23:4788–4797. https://doi.org/10.1111/gcb.13724
Nord-Larsen T (2002) Stand and site productivity response following whole-tree harvesting in early thinnings of Norway spruce (*Picea abies* (L.) Karst.). Biomass Bioenergy 23:1–12. https://doi.org/10.1016/S0961-9534(02)00032-6
O'Neill BC, Oppenheimer M, Warren R, Hallegatte S, Kopp RE, Pörtner HO, Scholes R, Birkmann J, Foden W, Licker R, Mach KJ, Marbaix P, Mastrandrea MD, Price J, Takahashi K, Van Ypersele JP, Yohe G (2017) IPCC reasons for concern regarding climate change risks. Nat Clim Chang 7:28–37. https://doi.org/10.1038/nclimate3179
Paşnicu D, Ghenţa M, Matei A (2019) Transition to bioeconomy: Perceptions and behaviors in Central and Eastern Europe. Amfiteatru Econ 21:9–23
Pelli P, Haapala A, Pykäläinen J (2017) Services in the forest-based bioeconomy–analysis of European strategies. Scand J For Res 32:559–567. https://doi.org/10.1080/02827581.2017.1288826
Peng C, Jiang H, Apps MJ, Zhang Y (2002) Effects of harvesting regimes on carbon and nitrogen dynamics of boreal forests in central Canada: a process model simulation. Ecol Model 155:177–189. https://doi.org/10.1016/S0304-3800(02)00134-5
Peng C, Ma Z, Lei X, Zhu Q, Chen H, Wang W, Liu W, Li W, Fang X, Zhou X (2011) A drought-induced pervasive increase in tree mortality across Canada's boreal forests. Nat Clim Chang 1:467–471. https://doi.org/10.1038/nclimate1293
Peyron JL, Maheut J (1999) Les fondements de l'économie forestière moderne: le rôle capital de Faustmann, il y a 150 ans, et celui de quelques-uns de ses précurseurs et successeurs. Rev For Fr LI:679–698. https://doi.org/10.4267/2042/5479
Points A (2018) Nordic Bioeconomy Programme. Nordic Council of Ministers, Copenhagen. https://doi.org/10.6027/ANP2018-785
Price C (2014) Temporal aspects in forest economics. In: Kant S, Alavalapati JRR (eds) Handbook of forest resource economics. Routledge, London
Pukkala T (2016) Which type of forest management provides most ecosystem services? For Ecosyst 3:1–16. https://doi.org/10.1186/s40663-016-0068-5

Reineke LH (1933) Perfecting a stand-density index for even-aged forests. J Agric Res 46:627–638

Sáenz-Romero C, Lamy JB, Ducousso A, Musch B, Ehrenmann F, Delzon S, Cavers S, Chałupka W, Dağdaş S, Hansen JK, Lee SJ, Liesebach M, Rau HM, Psomas A, Schneck V, Steiner W, Zimmermann NE, Kremer A (2017) Adaptive and plastic responses of Quercus petraea populations to climate across Europe. Glob Chang Bio 23:2831–2847. https://doi.org/10.1111/gcb.13576

Saint-André L, Buée M, Aubert M, Richter C, Deleuze C, Rakotoarison H, Abildtrup J, Akroume E, Bach C, Berthe T, Bilot N, Bouvet A, Chauvat M, Dreyfus P, Echevarria G, Elie F, Fauchery L, Fuente P, Gérant D, Lauvin D, Leban JM, Leblanc M, Leduc V, Maillard F, Normand M, Quibel E, Raveloson C, Renaud JP, Roy SJ, Stenger A, Viaud P, Vincenot L, Zeller B (2019). RESPIRE – Récolte des menus bois en forêt - Potentiel, Impact, Indicateurs et remédiations par épandage de cendres de bois, ADEME, Angers. Available via DIALOG. www.ademe.fr/sites/default/files/assets/documents/rapport-respire-recolte-bois-foret-2019.pdf. Accessed 16 Jul 2019

Samuelson PA (1976) Economics of forestry in an evolving society. Econ Inq 14:466–492. https://doi.org/10.1111/j.1465-7295.1976.tb00437.x

Sauter PA, Mußhoff O (2018) What is your discount rate? Experimental evidence of foresters' risk and time preferences. Ann For Sci 75:1–14. https://doi.org/10.1007/s13595-017-0683-5

Spinelli R, Magagnotti N (2010) Comparison of two harvesting systems for the production of forest biomass from the thinning of Picea abies plantations. Scand J For Res 25:69–77

Taccoen A, Piedallu C, Seynave I, Perez V, Gégout-Petit A, Nageleisen LM, Bontemps JD, Gégout JC (2019) Background mortality drivers of European tree species: climate change matters. Proc R Soc B Biol Sci 286:20190386. https://doi.org/10.1098/rspb.2019.0386

Terreaux JP (2008) Taux d'actualisation décroissants et cohérence temporelle des décisions de sylviculture. Rev For Fr 60:467–476. https://doi.org/10.4267/2042/21904

Terreaux JP (2018) N'oublions pas le futur : Valeurs, justice et taux d'actualisation. Eth Econ 15:67–80

Terreaux JP, Chavet M (2016) Risque de tempête et viabilité : une approche économique de l'aménagement forestier. RDV Tech ONF 51-52:49–52

Thiffault E, Hannam KD, Pare D, Titus BD, Hazlett PW, Maynard DG, Brais S (2011) Effects of forest biomass harvesting on soil productivity in boreal and temperate forests - A review. Environ Rev 19: 278–309. https://doi.org/10.1139/a11-009

Triska FJ, Cromack K (1980) The role of wood debris in forests and streams. Forests: fresh perspectives from ecosystem analysis. Oregon State Univ Press, 171-190

UN General Assembly (2015) Sustainable development goals. In Transforming Our World: The 2030 Agenda for Sustainable Development. UN, New York. Available via DIALOG. www.unfpa.org/sites/default/files/resource-pdf/Resolution_A_RES_70_1_EN.pdf. Accessed 30 Nov 2017

Van Mantgem PJ, Stephenson NL, Byrne JC, Daniels LD, Franklin JF, Fulé PZ, Harmon ME, Larson AJ, Smith JM, Taylor AH, Veblen TT (2009) Widespread Increase of Tree Mortality Rates in the Western United States. Science 323:521–524. https://doi.org/10.1126/science.1165000

Vasary V (2019) Knowledge-based agriculture in Central and Eastern European Countries' bioeconomy. Econ Environ Stud 19:137–154

Venanzi R, Picchio R, Piovesan G (2016) Silvicultural and logging impact on soil characteristics in Chestnut (Castanea sativa Mill.) Mediterranean coppice. Ecol Eng 92:82–89. https://doi.org/10.1016/j.ecoleng.2016.03.034

Wall A (2012) Risk analysisz of effects of whole-tree harvesting on site productivity. For Ecol Manag 282:175–184. https://doi.org/10.1016/j.foreco.2012.07.012

Weetman GF, Webber B (1972) The influence of wood harvesting on the nutrient status of two spruce stands. Can J For Res 2:351–369. https://doi.org/10.1139/x72-054

Westerling AL, Hidalg HG, Cayan DR, Swetnam TW (2006) Warming and Earlier Spring Increase Western U.S. Forest Wildfire Activity. Sci 313:940–943. https://doi.org/10.1126/science.1128834

Williams AP, Allen CD, Macalady AK, Griffin D, Woodhouse CA, Meko DM, Swetnam TW, Rauscher SA, Seager R, Grissino-Mayer HD, Dean JS, Cook ER, Gangodagamage C, Cai M, McDowell NG (2013) Temperature as a potent driver of regional forest drought stress and tree mortality. Nature Clim Change 3:292–297. https://doi.org/10.1038/nclimate1693

Wolfslehner B, Linser S, Pülzl H, Bastrup-Birk A, Camia A, Marchetti M (2016) Forest bioeconomy–a new scope for sustainability indicators. From science to policy: 4. European Forest Institute