Journal of Environmental Management 344 (2023) 118751

Contents lists available at ScienceDirect

Journal of Environmental Management

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

Research article

Climate-related subsidies for CO_2 absorption and fuel substitution: Effects on optimal forest management decisions

Zohreh Mohammadi [*,1], Peter Lohmander [1], Jan Kašpar, Meryem Tahri, Róbert Marušák

Faculty of Forestry and Wood Sciences, Czech University of Life Sciences Prague, Praha-Suchdol, Czech Republic

ARTICLE INFO

Keywords:
Uneven-aged forest
Carbon sequestration
Carbon substitution
Global warming
Optimal harvesting
Stand-level

ABSTRACT

This study investigates rational ways to optimize stand-level management decisions from an economic perspective to adjust alternative subsidies, aiming to reduce the CO_2 level in the atmosphere and consequently, to mitigate the global warming impacts. An objective function consisting of two parts is used to maximize the current production value that forests represent and the value of forests under the effects of different types of subsidies intended to reduce CO_2 levels. The optimal ways of adjusting stand-level management decisions are determined using a general comparative statics analysis, which takes into account alternative forms of climate-related subsidies. The optimal changes to stand-level management decisions are functions of the initial conditions of the stand of trees on which the decision will be made. The results have shown that there are one or two of the alternative forms of CO_2 subsidies increase: if the initially optimal values of the stock level after harvesting $\{V_1\}$ is lower than the stock level that maximizes the sustainable yield $\{V_{MSY}\}$, and the time interval between harvests $\{t\}$ is sufficiently short, then the initially optimal value of V_1 and t increase; if the initially optimal value of V_1 is lower than V_{MSY}, and t is sufficiently long, then the initially optimal values of V_1 and t may vary or stay unchanged; if the initially optimal value of V_1 is equal to V_{MSY}, and t is very short, then V_1 and t are not changed; if the initially optimal value of V_1 is higher than V_{MSY}, and/or t is sufficiently long, then the initially optimal values of V_1 and t decrease. Our approach of providing decisions at the stand-level can be extended to the broader scales at forest landscapes to address the related challenges.

1. Introduction

The increasing level of carbon dioxide (CO_2) in the atmosphere is a significant threat to planet Earth because it contributes to global warming. Lohmander (2020a) developed a differential equation model based on historical industrial emissions and observations of CO_2 levels in the atmosphere. The model explains the dynamic relationships of CO_2 levels and can be used to determine the consequences that various changes to global emissions strategies would entail. The optimal principles to apply in making adjustments to general forestry strategies in order to counteract global warming problems are presented by Lohmander (2020b) and (2020c), in which the research investigates whether expanding active forests can contribute to reducing the CO_2 level in the atmosphere. Forests can help alleviate climate change in various ways, for instance by storing carbon in forest ecosystems and producing a renewable supply of material and energy products (Gustavsson et al., 2021). Forests also counteract global warming by absorbing CO_2 emissions from fossil fuels (Pugh et al., 2019), and have a positive effect on climate change by providing harvested wood products to substitute fossil fuels and fossil-fuel-intensive materials, reducing anthropogenic emissions. However, using biomass as fuel releases CO_2 into the atmosphere, which affects the overall potential that forests represent for climate change mitigation, at least in the short term. In other words, in addition to carbon storage in forest ecosystems and harvested wood products, using wood to substitute fossil-fuel-intensive materials (product substitution) can have substantial benefits for the climate (Leskinen et al., 2018).

However, in order to gain a comprehensive understanding of the carbon sequestration potential of forests, it is essential to consider the role of individual stands within the broader forest ecosystem. Although an individual stand may not contain a large volume of wood or carbon compared to the forest ecosystem, it still plays a pivotal role in the carbon cycle (Liu and Han, 2009). Sequential harvesting of a proportion of stand-level wood and its subsequent use as a substitute for fossil fuels

* Corresponding author.
E-mail address: Mohammadiz@fld.czu.cz (Z. Mohammadi).
[1] These two authors contributed equally to this work.

https://doi.org/10.1016/j.jenvman.2023.118751
Received 18 May 2023; Received in revised form 21 July 2023; Accepted 9 August 2023
Available online 11 August 2023

in various type of industry mitigates the amount of CO_2 release into the atmosphere, especially over longer temporal scales (Mader, 2007; Liu and Han, 2009).

Previous works have demonstrated that harvested wood products benefit the climate by eliminating the emissions linked to fossil-fuel-intensive materials and by storing carbon (Soimakallio et al., 2016; Alam et al., 2017; Hiltunen et al., 2021; Gustavsson et al., 2021; Valatin, 2022).

Optimization can be described, in general, as achieving the best results with the available resources, either by minimizing or maximizing an objective criterion or by minimizing the number of resources needed to achieve a given objective. Forest management decisions can be optimized using, different scales at tree, stand, and forest landscape-level, and resolution in the decision space and in the state space.

In some studies, e.g., Lohmander (1988a), (1989), the analysis is based on continuous descriptions of these spaces. In others, the details of the harvest schedule and dynamic and periodic time path of the stock level are important for optimization, e.g., Lohmander (1992a), (1992b) and Lohmander and Mohammadi (2008).

Stand-level management policies can be optimized (Lohmander, 1988a, 2000, 2007): by assuming certainty, risk, or uncertainty for continuous cover forestry (Lohmander and Fagerberg, 2022) or by rotation forestry (Lohmander, 1988b, 1990, 1991). Multi-objective optimization techniques have been previously employed in stand-level management to assess various ecosystem services (Diaz-Balteiro et al., 2017). For instance, Johnston and Withey (2017) examined the economic and ecological outcomes of uneven-aged forest management by considering the value of carbon and random disturbances. Their study focused on stand-level optimization strategies. By incorporating carbon offsets into a Markov decision process (MDP) model, they found trade-offs between economic and ecological results over the long term. The research emphasized the sensitivity of optimal decisions to carbon prices, influencing ecological outcomes in forest management. Susaeta et al. (2022) conducted a study on stand-level optimization, determining the economic revenues and optimal forest management of uneven-aged loblolly pine, longleaf pine, and slash pine forests in the southeastern United States. Their analysis considered both timber and carbon benefits, examining the profitability and management strategies for the stands of these three pine species. Mohammadi Limaei and Mohammadi (2023) evaluated optimal forest harvesting practices in an uneven-aged forest in northern Iran, focusing specifically on economic and environmental objectives at stand-level, using Stochastic dynamic programming (SDP).

The optimal management of forest resources may require incorporating climate impacts on ecosystem productivity and harvesting rates. Climate change may have diverse effects on forest development and biodiversity through various mechanisms and interactions. In Europe, the projected impacts of climate change include a reduction in species ranges, alterations in forest productivity, increased natural and anthropogenic disturbances, and a decrease in the economic value of forest ecosystems.

Significant climate benefits are derived from strategies that target high forest productivity and harvest levels, and efficient use of harvested woody biomass to substitute carbon-intensive energy and materials. The objective function is the sum of the economic net present value of wood production and the values of the climate effects. The values of climate effects are determined in respect of alternative forms of CO_2 subsidies motivated by the desire to reduce the level of CO_2 in the atmosphere and, consequently, global warming.

This research goes beyond assessing the optimal production and substitution levels in stand-level management. It explores the complexities of dynamic forestry decisions to examine, e.g., how changes in climate-related CO_2 subsidies impact induced by the types and levels of the following influential factors. These factors include the optimal stock level after harvesting, the optimal time interval between partial harvests, and the optimal harvest volumes at different time scales. The significance of this research lies in its ability to enhance our understanding of trade-off linkages within forest ecosystems and provide decision-makers with valuable insights to make informed, optimal decisions.

2. Problem definition

The objective function π (V_1, t) is studied, with V_1 representing the stock level immediately after harvest, for each harvest, length t is the time interval between harvests, and V_2 the stock level immediately before harvesting for identical harvests carried out sequentially. These variables and dynamic connections are illustrated in Fig. 1.

The objective function contains two parts, π_A and π_B. The first part represents the present economic value of forest production. The second part is the value of forestry activities that reduce the CO_2 level in the atmosphere in different ways.

The value of the forest in terms of CO_2 is separated into two parts. The first is a climate value relating to the large volume of carbon not released into the atmosphere as CO_2 as a result of retaining a large volume of wood in the forest, i.e., the climate value of retaining a large volume of timber in the forest. The second value is also climate-related; if some of this timber, when harvested sequentially, is used in power stations and as fuel for cars, etc. Instead of fossil fuels such as coal and/or oil, these substituted fossil fuels remain underground and are not released into the atmosphere in the form of CO_2. This second value for forests can be much greater than the initial CO_2 effect in the long term. π_A and π_B are both functions of V_1 and t. ϵ is also introduced, representing a very short interval time. For more details see Supplementary Materials S.1.1.

$$\pi(V_1, t) = \pi_A(V_1, t) + \pi_B(V_1, t), V_1 > 0, 0 < \varepsilon \lll t, \varepsilon \approx 0 \tag{1}$$

The initial stock level before harvesting is V_0. This volume remains practically constant for the very short interval lengths.

$$V(s) \approx V_0 \quad 0 \leq s < \varepsilon_1 < \varepsilon \tag{2}$$

The first harvest takes place after an interval of length ϵ_2, removing a volume of wood, h_0, from the forest.

$$V(\varepsilon) = V_0 - h_0, \varepsilon \geq \varepsilon_1 + \varepsilon_2 \tag{3}$$

At time ϵ, the remaining stock level is $V(\epsilon)$, which can also be denoted V_1. The stock level then increases over time until the next harvest. See Fig. 1.

$$\frac{dV(s)}{ds} > 0, \varepsilon \leq s < t + \varepsilon \tag{4}$$

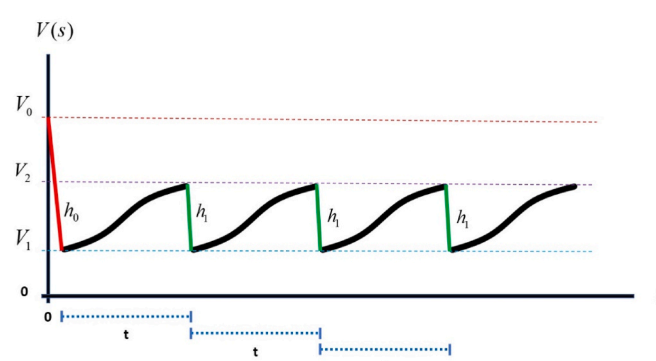

Fig. 1. The graph illustrates the time path of stock level V(s) as a function of time s. Before the harvest sequence starts, the initial value of V(s) is V_0. The first harvest volume, h_0, reduces the stock level to V_1. The stock is then left to grow for a time interval of length t. When the stock reaches level V_2, the next harvest, of volume h_1, takes the stock level back down to V_1. An indefinite number of identical growth-and-harvest cycles follows.

$$h_0 = V_0 - V_1 \tag{5}$$

$$V_1 = V(\varepsilon) \tag{6}$$

At time $t + \varepsilon$, the stock level reaches V_2, which can be considered a function of V_1 and t.

$$V_2 = V_2(V_1, t) \tag{7}$$

The volume harvested repeatedly from the forest after the initial harvest h_0, is h_1. This can also be considered a function of V_1 and of t.

$$h_1 = V_2(V_1, t) - V_1 \tag{8}$$

The harvest path h(s) is therefore periodic and mostly has a zero value.

$$h(s) = 0, \forall s \neq kt + \varepsilon, k \in \{0, 1, 2, \ldots, n\}, n \rightarrow \infty \tag{9}$$

In every cycle, the stock level returns to the level immediately before harvesting.

$$V_2 = V(kt + s + \varepsilon) = V(s + \varepsilon), \forall \varepsilon \leq s \leq t, k \in \{0, 1, 2, \ldots, n\}, n \rightarrow \infty \tag{10}$$

In every cycle, the stock level also returns to the level immediately after harvesting.

$$V_1 = V(kt + \varepsilon) = V(t + \varepsilon), \forall k \in \{0, 1, 2, \ldots, n\}, n \rightarrow \infty \tag{11}$$

The time path of stock level V(s) is illustrated in Fig. 1.

2.1. Maximization problem

To maximize the objective function, the two decision variables V_1 and t are used. This problem is shown in (12). The first part of the objective function, π_A, is the present value of forest production. The first harvest has the variable net price (price reduced by variable costs) P_{A0}. C is the setup cost. In the following sequence of harvests, the net price is P_{A1}. The rate of interest in continuous time is denoted r. P_{B1} and P_{B2} are prices that represent the CO_2 effects of forestry. P_{B1} represents the price paid for the reduction in CO_2 emissions achieved through active forestry and substitution operations, while P_{B2} represents the price paid for the amount of fossil fuels that can remain underground due to these operations. These prices are used to calculate the profitability of the forest optimization problem and can be adjusted to study the effect of changes in the CO_2 market on the optimal harvest interval and optimal stock level after harvest.

$$\max_{V_1,t} \pi(V_1, t) = P_{A_0}(V_0 - V_1) - c + \frac{P_{A_1}(V_2(V_1, t) - V_1) - c}{e^{rt} - 1} + P_{B_1} V_0 \int_0^\infty e^{-r_2 s} ds + \frac{(V_2(V_1, t) - V_1)}{t} \int_0^\infty e^{-r_2 s}(P_{B_1} s + P_{B_2}) ds \tag{12}$$

We develop the suitable forms for the two first-order optimum conditions. For more details see Supplementary Materials S.1.2.

$$\frac{d\pi}{dV_1} = -P_{A_0} + \left(\frac{P_{A_1}}{e^{rt} - 1} + \frac{\int_0^\infty e^{-r_2 s}(P_{B_1} s + P_{B_2}) ds}{t} \right) \left(\frac{dV_2}{dV_1} - 1 \right) = 0 \tag{13}$$

$$\frac{d\pi}{dt} = \frac{P_{A_1} \frac{dV_2}{dV_1}(e^{rt} - 1) - (P_{A_1}(V_2(V_1, t) - V_1) - c) re^{rt}}{(e^{rt} - 1)^2} + \frac{\int_0^\infty e^{-r_2 s}(P_{B_1} s + P_{B_2}) ds}{t} \left(\frac{dV_2}{dt} - \frac{(V_2(V_1, t) - V_1)}{t} \right) = 0 \tag{14}$$

2.1.1. Observations of some second-order derivatives and second-order maximum conditions

It is not sufficient to know the first-order optimum conditions to ensure that a maximum has been reached and/or determine whether it is unique; the second-order maximum conditions must also be investigated. In general, it is difficult to determine whether the second-order conditions are satisfied without several explicit assumptions about functional forms. Some parts of the second-order conditions, however, can be determined easily:

$$\frac{d^2\pi}{dV_1^{\,2}} = \left(\frac{P_{A_1}}{e^{rt} - 1} + \frac{\int_0^\infty e^{-r_2 s}(P_{B_1} s + P_{B_2}) ds}{t} \right) \frac{d^2 V_2}{dV_1^{\,2}} < 0, \tag{15}$$

$$r > 0, t > 0, P_{A_1} > 0, P_{B1} \geq 0, P_{B_2} \geq 0, \frac{d^2 V_2}{dV_1^{\,2}} < 0$$

The value of $\frac{d^2\pi}{dt^2}$ is more complicated to determine without making certain assumptions about functional forms. However, a unique maximum is assumed.

$$\left| \frac{d^2\pi}{dt^2} \right| < 0, \begin{vmatrix} \frac{d^2\pi}{dV_1^{\,2}} & \frac{d^2\pi}{dV_1 dt} \\ \frac{d^2\pi}{dt dV_1} & \frac{d^2\pi}{dt^2} \end{vmatrix} > 0 \tag{16}$$

2.2. Comparative statics analysis

It can now be determined how the optimal forestry decisions are affected by parameter changes. The optimal harvest interval and optimal stock level directly after harvest were studied to see how they are affected by possible changes to the two CO_2-related prices denoted P_{B1} and P_{B2}.

2.2.1. Comparative statics analysis in the time interval dimension

First, the optimal changes of the time interval between harvest t* were investigated, and the stock level V_1 directly after harvesting left constant. B represents B_1 and B_2.

$$\frac{d^2\pi}{dt^2} dt^* + \frac{d^2\pi}{dt dP_B} dP_B = 0 \tag{17}$$

Equation (18) developed from equation (17). For more details see Supplementary Materials S.1.3.

$$\frac{d^2\pi}{dt dP_{B_2}} = \frac{\int_0^\infty e^{-r_2 s} ds}{t} \left(\frac{dV_2}{dt} - \frac{(V_2(V_1, t) - V_1)}{t} \right) \tag{18}$$

The sustainable yield, with continuous harvesting, is a strictly concave function of the stock level. MSY denotes the unique maximum sustainable yield. V_{MSY} denotes the stock level that maximizes the sustainable yield.

Observation: $t > 0 \wedge t \rightarrow 0.$ $\left(\frac{dV_2}{dt} - \frac{(V_2(V_1,t) - V_1)}{t} \right)$ is strictly positive for low values of V, zero for the MSY maximizing value of V, V_{MSY}, and strictly negative for higher values of V.

$$\frac{d^2\pi}{dt dP_{B_1}} = \begin{cases} > 0 & \text{if} \quad V_2 < V_{MSY} \\ = 0 & \text{if} \quad V_2 = V_{MSY} \\ < 0 & \text{if} \quad V_2 > V_{MSY} \end{cases} \Rightarrow \frac{dt^*}{dP_{B_1}} = \begin{cases} > 0 & \text{if} \quad V_2 < V_{MSY} \\ = 0 & \text{if} \quad V_2 = V_{MSY} \\ < 0 & \text{if} \quad V_2 > V_{MSY} \end{cases} \tag{19}$$

$$\frac{d^2\pi}{dt dP_{B_2}} = \begin{cases} > 0 & \text{if} \quad V_2 < V_{MSY} \\ = 0 & \text{if} \quad V_2 = V_{MSY} \\ < 0 & \text{if} \quad V_2 > V_{MSY} \end{cases} \Rightarrow \frac{dt^*}{dP_{B_2}} = \begin{cases} > 0 & \text{if} \quad V_2 < V_{MSY} \\ = 0 & \text{if} \quad V_2 = V_{MSY} \\ < 0 & \text{if} \quad V_2 > V_{MSY} \end{cases} \tag{20}$$

Therefore, if P_{B1} and/or P_{B2} increase(s) and everything else remains the same, the optimal harvest interval increases if $V_2 < V_{MSY}$. The optimal harvest interval is not changed if $V_2 = V_{MSY}$, and the optimal harvest interval decreases if $V_2 > V_{MSY}$. Figs. 2 and 3 are a graphic illustration of the principles of the comparative statics analysis summarized in equations (19) and (20).

2.2.2. Comparative statics analysis in the volume dimension

The optimal change of the decision is now evaluated, where the optimal stock level is only changed directly after harvest V_1^*, and the time interval between harvests is left constant. The effects of changes to P_{B1} on V_1^* is based on equation (21) as follows: (more details in Supplementary Materials S.1.4.)

$$\frac{dV_1{}^*}{dP_{B_1}} = \frac{-\frac{d^2\pi}{dV_1 dP_{B_1}}}{\frac{d^2\pi}{dV_1{}^2}} \tag{21}$$

The influences of P_{B2} on V_1^* was investigated by equation (22). For more details see Supplementary Materials S.1.4.

$$\frac{dV_1{}^*}{dP_{B_2}} = \frac{-\frac{d^2\pi}{dV_1 dP_{B_2}}}{\frac{d^2\pi}{dV_1{}^2}} \tag{22}$$

To derive the signs of (21) and (22), more information is needed concerning the growth function. It is assumed that growth, at least locally, can be approximated by the logistic equation:

$$V_2 = V_2(V_1, t) \tag{23}$$

The following equation is derived and explained in detail by Lohmander and Zazykina (2010). It can be considered as an application of the formula developed by Verhulst (1838) (Bacaër, 2011). K denotes the carrying capacity of the environment. $\lim_{t\to\infty} V_2 = K$, which follows from (24).

$$V_2 = V_2(V_1, t; .) = \frac{1}{\frac{1}{K} + \left(\frac{1}{V_1} - \frac{1}{K}\right)e^{-at}}, a > 0, t > 0 \tag{24}$$

$$V_2 - V_1 = \frac{1}{\frac{1}{K} + \left(\frac{1}{V_1} - \frac{1}{K}\right)e^{-at}} - V_1 \tag{25}$$

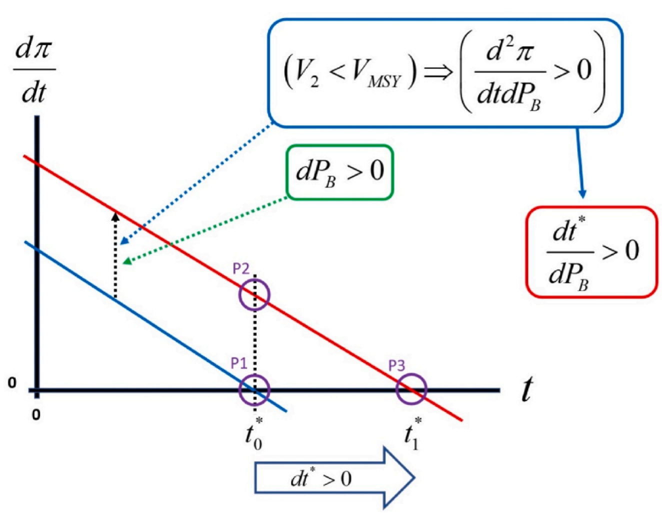

Fig. 2. The graph illustrates part of the comparative statics analysis. If the value of V_2 is lower than the stock level that would maximize the sustainable yield with continuous harvesting, V_{MSY}, then the optimal time interval between harvests, t*, is a strictly increasing function of the climate-related price P_B, which represents P_{B1} and P_{B2}. The optimal solution moves from P_1, via P_2, to P_3. See equations (19) and (20).

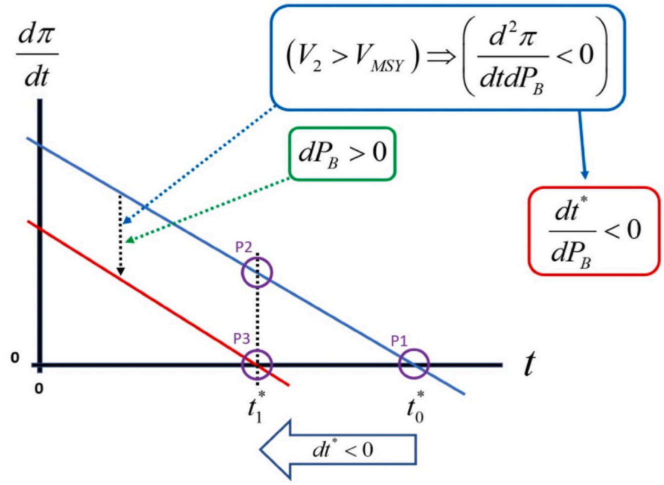

Fig. 3. The graph illustrates part of the comparative statics analysis. If the value of V_2 is higher than the stock level that would maximize the sustainable yield, V_{MSY}, with continuous harvesting, then the optimal time interval between harvests, t*, is a strictly decreasing function of climate-related price P_B, which represents P_{B1} and P_{B2}. The optimal solution moves from P_1, via P_2, to P_3. See equations (19) and (20).

$$\frac{d(V_2 - V_1)}{dV_1} = \frac{dV_2}{dV_1} - 1 \tag{26}$$

$$\frac{dV_2}{dV_1} - 1 = \frac{(1 - e^{at})\left(V_1{}^2 e^{at} - (K - V_1)^2\right)}{(V_1 e^{at} + K - V_1)^2} \tag{27}$$

If we assume that $at > 0 \Rightarrow (1 - e^{at}) < 0 \Rightarrow$ therefore, equation (28) is concluded.

$$\text{sgn}\left(\frac{dV_2}{dV_1} - 1\right) = \text{sgn}\left(-\left(V_1{}^2 e^{at} - (K - V_1)^2\right)\right) \tag{28}$$

From (S1) and (28), we can derive (29). For more details see Supplementary Materials S.1.5.

$$\text{sgn}\left(\frac{d^2\pi}{dV_1 dP_B}\right) = \text{sgn}\left(V_1{}^2(1 - e^{at}) + K^2 - 2KV_1\right) \tag{29}$$

2.3. Calculations with very short time intervals

If we assume that $t \to 0 \Rightarrow (1 - e^{at}) \to 0 \wedge V_2 - V_1 \to 0$ Hence, for very short time intervals, $V \approx V_1 \approx V_2$. Therefore the optimal changes with a very short interval were calculated as in the following equation (30):

$$\text{sgn}\left(\frac{d^2\pi}{dV_1 dP_{B_1}}\right) = \text{sgn}\left(\frac{d^2\pi}{dV_1 dP_{B_2}}\right) = \text{sgn}\left(K^2 - 2KV\right) \tag{30}$$

if we assume that $K > 0$, the optimal changes with a very short interval are calculated as in the following equation (31):

$$\text{sgn}\left(\frac{d^2\pi}{dV_1 dP_{B_1}}\right) = \text{sgn}\left(\frac{d^2\pi}{dV_1 dP_{B_2}}\right) = \text{sgn}(K - 2V) = \text{sgn}\left(\frac{K}{2} - V\right) \tag{31}$$

Consequently, in order to evaluate the optimal changes, three observations were studied:

If $V \approx V_1 \approx V_2 < V_{MSY}$ the optimal changes with a very short interval were greater than zero as in the following eaquation (32):

$$\text{sgn}\left(\frac{d^2\pi}{dV_1 dP_{B_1}}\right) = \text{sgn}\left(\frac{d^2\pi}{dV_1 dP_{B_2}}\right) > 0 \tag{32}$$

If $(V \approx V_1 \approx V_2 = V_{MSY})$ the optimal changes with a very short interval were equal zero as in the following equation (33):

$$\operatorname{sgn}\left(\frac{d^2\pi}{dV_1 dP_{B_1}}\right)=\operatorname{sgn}\left(\frac{d^2\pi}{dV_1 dP_{B_2}}\right)=0 \tag{33}$$

If $V \approx V_1 \approx V_2 > V_{MSY}$ the optimal changes with a very short interval were less than zero as in the following equation (34):

$$(V \approx V_1 \approx V_2 > V_{MSY}) \Rightarrow \operatorname{sgn}\left(\frac{d^2\pi}{dV_1 dP_{B_1}}\right)=\operatorname{sgn}\left(\frac{d^2\pi}{dV_1 dP_{B_2}}\right)<0 \tag{34}$$

2.4. Calculations with longer time intervals

If t increases from zero, then $(1-e^{at})$ becomes more negative. As a result, $(V_1^2(1-e^{at})+K^2-2KV_1)$ becomes more negative.

$\operatorname{sgn}\left(\frac{d^2\pi}{dV_1 dP_{B_1}}\right)=\operatorname{sgn}\left(\frac{d^2\pi}{dV_1 dP_{B_2}}\right)$ and $\left(\frac{dV_2}{dV_1}-1\right)$ may become strictly negative even if $V_1 \le \frac{K}{2}$.

2.5. Conclusions in the volume dimension

According to equations (32)–(35), as $t \to 0$: $\frac{dV_1^*}{dP_{B_1}}=\frac{-\frac{d^2\pi}{dV_1 dP_{B_1}}}{\frac{d^2\pi}{dV_1^2}}$ and $\frac{dV_1^*}{dP_{B_2}}=\frac{-\frac{d^2\pi}{dV_1 dP_{B_2}}}{\frac{d^2\pi}{dV_1^2}}$ are strictly positive for $V < V_{MSY}$, zero for $V = V_{MSY}$ and strictly negative for $V > V_{MSY}$. These results are illustrated in Figs. 4 and 5.

If the time interval is not very short, $\frac{dV_1^*}{dP_{B_1}}=\frac{-\frac{d^2\pi}{dV_1 dP_{B_1}}}{\frac{d^2\pi}{dV_1^2}}$ and $\frac{dV_1^*}{dP_{B_2}}=\frac{-\frac{d^2\pi}{dV_1 dP_{B_2}}}{\frac{d^2\pi}{dV_1^2}}$ are strictly positive for low values of V_1, zero for a particular value of V_1, $V_1 < V_{MSY}$ and strictly negative for larger values of V_1.

2.6. Comparative statics analysis in two dimensions

In the derivations below, the qualitative effects (direction of changes) of the decision variables are investigated if the imaginary parameter P_B should increase, representing P_{B1} and P_{B2}. Since $\operatorname{sgn}\left(\frac{d^2\pi}{dV_1 dP_{B_1}}\right)=\operatorname{sgn}\left(\frac{d^2\pi}{dV_1 dP_{B_2}}\right)$ and $\operatorname{sgn}\left(\frac{d^2\pi}{dtdP_{B_1}}\right)=\operatorname{sgn}\left(\frac{d^2\pi}{dtdP_{B_2}}\right)$, and since complementary assumptions are made (below), the results derived and reported below with respect to the imaginary parameter P_B are relevant

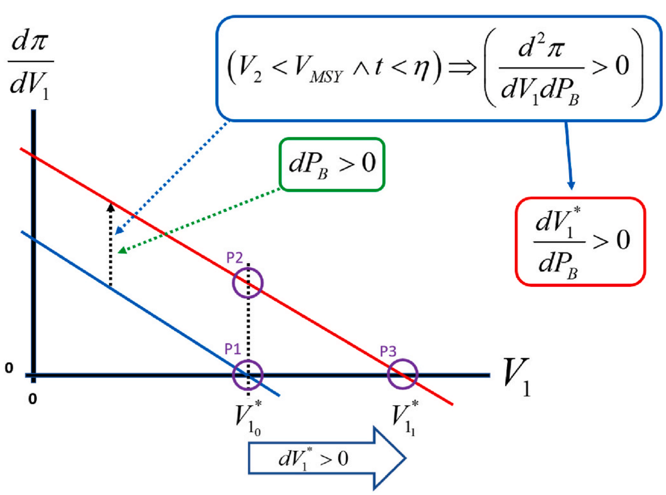

Fig. 4. The graph illustrates part of the comparative statics analysis. If the value of V_2 is lower than the stock level that would maximize the sustainable yield, V_{MSY}, with continuous harvesting, and the time interval between harvests is shorter than the short time interval $\eta > 0$, then the optimal stock level directly after harvesting, $V_1{}^*$, is a strictly increasing function of the climate related price P_B, which represents P_{B1} and P_{B2}. Note that the highest possible value of η, for which the signs of the derivatives remain constant, cannot be determined without very specific growth function information. The optimal solution moves from P_1, via P_2, to P_3.

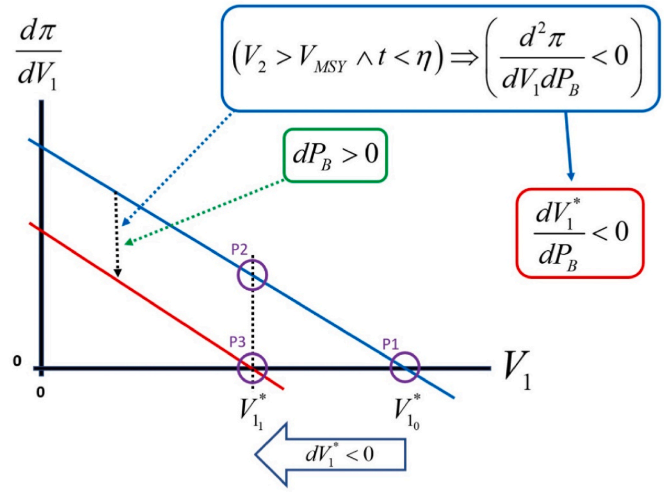

Fig. 5. The graph illustrates part of the comparative statics analysis. If the value of V_2 exceeds the stock level that would maximize the sustainable yield, V_{MSY}, with continuous harvesting, and the time interval between harvests is shorter than the short time interval $\eta > 0$, then the optimal stock level directly after harvesting, $V_1{}^*$, is a strictly decreasing function of the climate related price P_B, which represents P_{B1} and P_{B2}. Note that the exact value of the highest possible value of η, for which the signs of the derivatives remain constant, cannot be determined without very specific growth function information. The optimal solution moves from P_1, via P_2, to P_3.

to both parameters P_{B1} and P_{B2}.

$$\begin{bmatrix} \frac{d^2\pi}{dV_1^2} & \frac{d^2\pi}{dV_1 dt} \\ \frac{d^2\pi}{dtdV_1} & \frac{d^2\pi}{dt^2} \end{bmatrix}\begin{bmatrix} dV_1^* \\ dt^* \end{bmatrix}=\begin{bmatrix} -\frac{d^2\pi}{dV_1 dP_B}dP_B \\ -\frac{d^2\pi}{dtdP_B}dP_B \end{bmatrix} \tag{35}$$

The existence of a unique maximum is assumed.

$$\left|\frac{d^2\pi}{dV_1^2}\right|<0,\ \left|\frac{d^2\pi}{dt^2}\right|<0,\ |D|=\begin{vmatrix} \frac{d^2\pi}{dV_1^2} & \frac{d^2\pi}{dV_1 dt} \\ \frac{d^2\pi}{dtdV_1} & \frac{d^2\pi}{dt^2} \end{vmatrix}>0 \tag{36}$$

$$\frac{dV_1^*}{dP_B}=\frac{\begin{vmatrix} -\frac{d^2\pi}{dV_1 dP_B} & \frac{d^2\pi}{dV_1 dt} \\ -\frac{d^2\pi}{dtdP_B} & \frac{d^2\pi}{dt^2} \end{vmatrix}}{|D|}=\frac{-\frac{d^2\pi}{dV_1 dP_B}\frac{d^2\pi}{dt^2}+\frac{d^2\pi}{dtdP_B}\frac{d^2\pi}{dV_1 dt}}{|D|} \tag{37}$$

$$\frac{dt^*}{dP_B}=\frac{\begin{vmatrix} \frac{d^2\pi}{dV_1^2} & -\frac{d^2\pi}{dV_1 dP_B} \\ \frac{d^2\pi}{dtdV_1} & -\frac{d^2\pi}{dtdP_B} \end{vmatrix}}{|D|}=\frac{-\frac{d^2\pi}{dV_1^2}\frac{d^2\pi}{dtdP_B}+\frac{d^2\pi}{dtdV_1}\frac{d^2\pi}{dV_1 dP_B}}{|D|} \tag{38}$$

2.6.1. Special assumptions of relevance to the two-dimensional comparative statics analysis

$\frac{d^2\pi}{dtdV_1}=\varepsilon_1<0$. $ABS(\varepsilon_1)$ is very small. We have a unique maximum. $|D|>0$.

As a consequence,

$$\frac{dV_1^*}{dP_B}=\frac{\begin{vmatrix} -\frac{d^2\pi}{dV_1 dP_B} & \frac{d^2\pi}{dV_1 dt} \\ -\frac{d^2\pi}{dtdP_B} & \frac{d^2\pi}{dt^2} \end{vmatrix}}{|D|}=\frac{-\frac{d^2\pi}{dV_1 dP_B}\frac{d^2\pi}{dt^2}+\frac{d^2\pi}{dtdP_B}\varepsilon_1}{|D|}\approx\frac{-\frac{d^2\pi}{dV_1 dP_B}\frac{d^2\pi}{dt^2}}{|D|} \tag{39}$$

$$\frac{dt^*}{dP_B} = \frac{\begin{vmatrix} \frac{d^2\pi}{dV_1^2} & -\frac{d^2\pi}{dV_1dP_B} \\ \frac{d^2\pi}{dtdV_1} & -\frac{d^2\pi}{dtdP_B} \end{vmatrix}}{|D|} = \frac{-\frac{d^2\pi}{dV_1^2}\frac{d^2\pi}{dtdP_B} + \varepsilon_1\frac{d^2\pi}{dV_1dP_B}}{|D|} \approx \frac{-\frac{d^2\pi}{dV_1^2}\frac{d^2\pi}{dtdP_B}}{|D|} \quad (40)$$

$$\mathrm{sgn}\left(\frac{dV_1^*}{dP_B}\right) = \mathrm{sgn}\left(\frac{d^2\pi}{dV_1dP_B}\right) \quad (41)$$

$$\mathrm{sgn}\left(\frac{dt^*}{dP_B}\right) = \mathrm{sgn}\left(\frac{d^2\pi}{dtdP_B}\right) \quad (42)$$

3. Results

As found in the earlier part of this analysis, the partial derivatives (41) and (42) also gave the same signs when derived via comparative statics analysis based on one-dimensional optimization. If the initially optimal value of V_1 is lower than the stock level V_{MSY}, and the time interval between harvests t is sufficiently short, then the initially optimal values of V_1 and t increase if P_B (P_{B1} and/or P_{B2}) increase(s). If the initially optimal value of V_1 is lower than V_{MSY}, and t is sufficiently long, then V1 and t may increase, be unchanged, or decrease if P_B (P_{B1} and/or P_{B2}) increase(s). If the initially optimal value of V_1 is equal to V_{MSY}, and t is very short, then V_1 and t are not changed if P_B (P_{B1} and/or P_{B2}) increase(s). If the initially optimal value of V_1 is higher than V_{MSY}, and/or t is sufficiently long, then V_1 and t decrease if P_B (P_{B1} and/or P_{B2}) increase (s).

To assess the effectiveness of our proposed stand-level optimization framework, we conducted a study comprising five different scenarios. The primary objective of the study was to observe the trend of optimal values and determine how the optimal harvest interval and optimal stock level are impacted by possible changes to the two CO_2-related prices, P_{B1} and P_{B2}. Based on previous study in Sweden by Lohmander and Zazykina (2010), the initial stock level before harvesting, net wood price, setup cost, and real interest rate were considered as being 300 m^3 per ha, €20 per m^3, €50 per ha, and 0.03 respectively. In the first scenario (M_0), which we referred to as the Baseline scenario, it was assumed that no changes were made to the initial conditions and parameters. In the second scenario (M_1), the net wood price and setup cost as the first scenario were maintained, but the real interest rate was decreased to 0.02. In the third scenario (M_2), the price paid for reducing CO2 emissions was achieved through active forestry and substitution operations. We increased it to €0.5 per tonne of CO_2. In the fourth scenario (M_3), a significant increase in the price was paid for the reduction in CO_2 emissions achieved (an increase to €2 per tonne of CO_2), and in the final scenario (M_4), the price paid for the amount of fossil fuels was increased to €10 per tonne of CO_2. By analyzing these scenarios, we were able to gain insights into the behavior of the optimal values of the decision variables under different conditions. This information is invaluable for forest managers and policymakers seeking to optimize the use of forest resources while balancing economic and environmental factors.

To incorporate the stand-level optimization perspective, we considered a specific forest growth model with fixed parameter values, namely $a = 0.05$ and $K = 400$, based on the logistic growth function developed by Lohmander and Zazykina (2010) for a forest case study in Sweden. The following differential equation represents the forest growth model:

$$\dot{x} = \frac{dx}{dt} = \frac{1}{20}x - \frac{1}{8000}x^2 \quad (43)$$

In addition, the optimal stock level immediately after harvest, V_2, was determined based on equation (24) by Lohmander and Zazykina (2010):

$$V_2 = \frac{1}{\frac{1}{400} + \left(\frac{1}{30} - \frac{1}{400}\right) * e^{-0.05t}} \quad (44)$$

We used the LINGO software, a mathematical modeling and optimization tool to obtain the optimal solutions for each scenario. By solving the stand-level optimization problem, the optimal solutions for each scenario were obtained (Fig. 6).

Fig (6) demonstrates the comparative analysis between four different scenarios (M_0, M_1, M_2, M_3 and M_4) relating to the impact of raising the value of P_{B1} and P_{B2} on the optimal values of V_1 and t. The trend can be observed in the results of the comparison between the initially optimal scenario M_0 and scenarios M_1 and M_2, where P_{B1} is raised from 0 to 0.5. In both scenarios, an increase in the optimal value of V_1, relative to M_0, is observed, while a decrease in the optimal value of t is noted. It is suggested that an increase in P_{B1} may lead to an increase in the stock level (V_1) and a reduction in the interval between harvests (t), which can prove advantageous in the short term. The observed pattern can be discerned by comparing the outcomes of scenario M_2 with scenario M_3, in which the value of P_{B1} is raised from 0.5 to 2; the optimal value of V_1 continues to increase compared to M_2, while the optimal value of t decreases slightly. However, in scenario M_4, where P_{B2} is increased to 10, the optimal values of t decrease significantly compared to M_3.

4. Discussion

From a practical and applied perspective, it is often convenient to have a theoretical model that gives a simple answer to a question and is not dependent on several unknown conditions and parameters. With such a model, fewer investigations into the true nature of the situation are required, which saves on costs, and the results are more easily communicated. This paper shows that using comparative statics analysis, we cannot correctly answer crucial questions about optimal stand-level management decisions under adjusted CO_2 subsidies if important parameters in the forest management problems are unknown. The CO_2-related types of subsidies for forestry defined, analyzed and discussed in this paper are designed to enable reductions in global warming by reducing the CO_2 in the atmosphere as a result of rationally-adjusted stand-level management decisions.

There are two important, concrete applications for these new results, as follows:

Decisions made at the stand-level can provide significant implications to address challenges at broader scale of forest landscape. Large parts of the world, the interiors of the Russian Federation and Canada in particular, have very high stock levels and very long-time intervals between harvests, and some forest areas are never harvested at all. In these areas, the stock levels should be reduced and the time intervals between harvests shortened in order to reduce global warming, and subsidies to rational CO_2-related forests should be increased.

Chen et al. (2018) assessed the greenhouse gas effects of harvested wood products made from managed forests in Canada. Their results showed that sustainable forest harvesting reduces greenhouse gas emissions in the long term. Studies by Cintas et al. (2017) support our results. They confirmed that short rotations and more frequent harvests are often suggested as possible solutions to reduce carbon emissions into the atmosphere. Highly-stocked forest ecosystems will progressively become an undiscovered source of greenhouse gases in the future, with increasing forest age and stocking. With larger stocks and older forests, the potential CO_2 emissions are greater, according to studies by Seidl et al. (2014), Allen et al. (2015), Millar and Stephenson (2015), Seidl et al. (2017) and Thom and Seidl (2016). A study conducted by Forzieri et al. (2021) revealed that the wood stored in the ecosystem only 'compensates' for the rise in atmospheric fossil CO_2 without affecting emissions. Harvested wood, on the other hand, contributes to reducing the use of fossil fuels. In addition, eliminating fossil fuel use by product and energy substitution is permanent, while carbon storage in the ecosystem is temporary, given the liability of forest carbon stocks and associated risks. Harvesting highly-stocked forests also makes a positive contribution to substitution. Carbon loss from the biosphere occurs with decomposition and biomass burning. The scant recognition of on-site

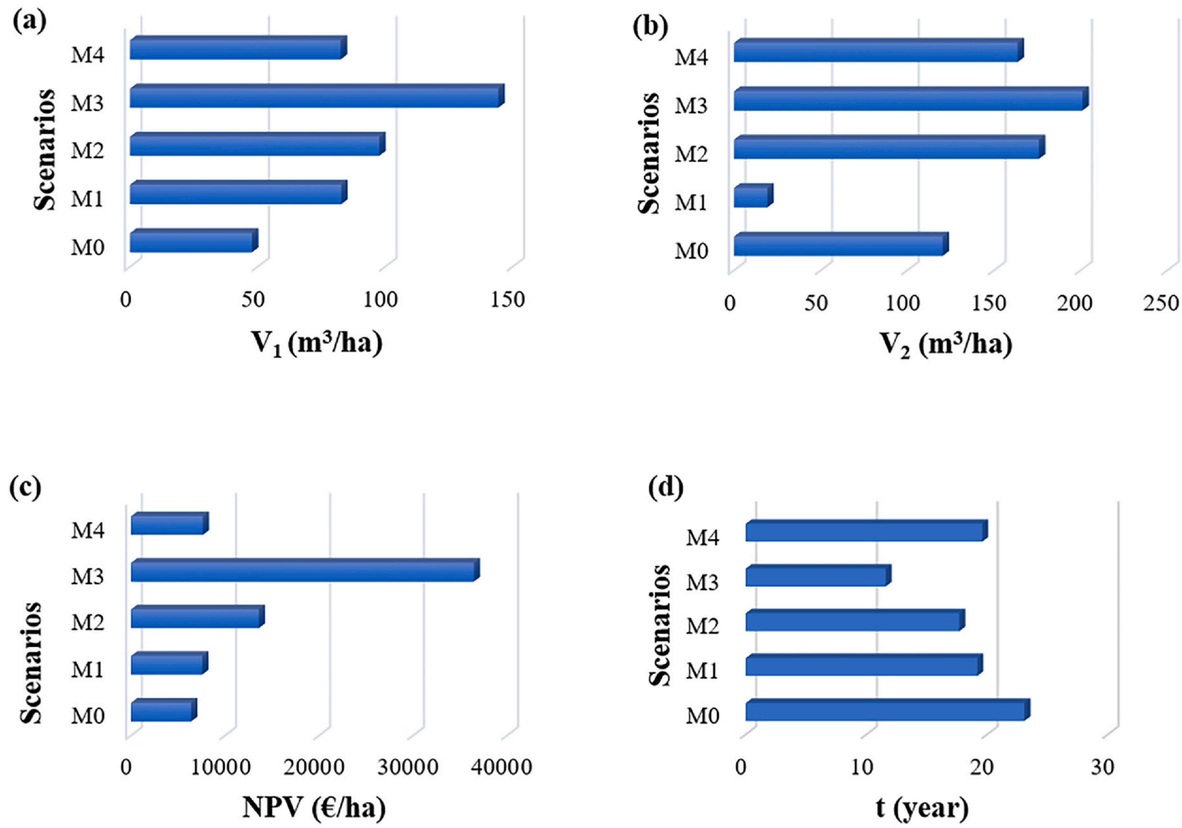

Fig. 6. Comparative analysis of four different scenarios (M_0, M_1, M_2, M_3 and M_4) concerning the impact of raising the value of P_{B1} and P_{B2} on the optimal values of V_1 (a), V_2 (b), NPV (c), and t (d).

forest-harvested products as a positive contribution to mitigating climate policy undermines the willingness of private owners and public bodies to take care of forests and the landscape (Schulze et al., 2022).

In the present analysis, however, we have seen that in areas with short time intervals between harvests and low stock levels, the optimal time intervals between harvests and stock levels after harvesting simultaneously increase under the influence of global warming and rationally-used CO_2 subsidies.

According to a study by Lin and Ge (2020), forests can generate carbon sinks without the harvests and bioenergy produced by wood products, by substituting fossil fuels with harvests. As a result, bioenergy generated from wood fuel from forests and carbon sinks are two important ways in which forests can alleviate climate change. Upmann and Behringer (2020) confirmed that a longer period of harvesting is required if the maximal harvesting rate is low. In this case, the maximal harvest rate is high, so the agent can afford to postpone the start of harvesting. It can be concluded that carbon neutrality has important implications for forest management: any net savings in emissions resulting from disturbances, by using harvested wood as biofuel to replace fossil fuels, for example, Butarbutar et al. (2016), can play a positive role in mitigating global climate change. In general, a balance must be found between the contribution that forests make to climate change mitigation and maintaining the many ecosystem services that forests provide (Molina et al., 2022).

5. Conclusions

The general principles of adjusting optimal, detailed, stand-level management, such as the time interval between harvests and the stock level directly after harvesting, to CO_2-related subsidies have been determined using general mathematical methods. This is a crucial step in the process of giving forest owners and forestry companies all over the world the economic motivation to use forest resources in the best possible way to combat the problem of global warming. The principles can be applied in any country where the fundamental parameters or relevance can be determined. The research topics suggested below are to be encouraged in the interest of an environmentally and economically rich and stable world.

For further advances in this field, we recommend our developed analytical optimization model to be applied into empirically- and numerically-based case studies, using forest data from different regions of the world, where uneven-aged silviculture is practiced. The model should also be generalized and extended to include adaptive control options and stochastic elements in the climate process. With this model structure, the latest predictable developments rather than earlier ones can also be managed sequentially. Other modeling approaches and general results relating to decision optimization problems of this type can also be explored in Lohmander (2019a, 2019b, and 2022), and Lohmander and Fagerberg (2022).

Credit author statement

Zohreh Mohammadi: Investigation, Methodology, Writing – original draft. Peter Lohmander: Conceptualization, Methodology, Writing – original draft. Jan Kašpar: Supervision, Project administration, Funding acquisition, Writing - review & editing. Meryem Tahri: Writing - review & editing. Róbert Marušák: Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Acknowledgements

This study was supported by the "**NAZV QK21010354 Progressive methods of forest management planning to support sustainable forest management**" project in the Czech University of Life Sciences Prague. The authors gratefully acknowledge Prof. Dr. Jason Michael Evans (Editor-in-Chief), Dr. David Roubaud (Associate Editor),and the anonymous reviewers for their scientific constructive comments.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2023.118751.

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