To clear-cut or not to clear-cut

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Cost-benefit analyses of post-fire management approaches in the Ljusdal fire-complex

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Abstract

Wildfires causes natural disturbances to ecosystems which can have potentially damaging results for ecosystem services and economic income from timber production. The post-fire management approach can be essential for the environmental work regarding the recovery of ecosystems and maintaining ecosystem services. The aim of this study was therefore to evaluate different post-fire management approaches of conventional forestry with clear-cutting, continuous cover forestry, and nature reserves with no management practice allowed, from an ecological, economic, and societal perspective. The focus area of this report was the Ljusdal fire sites, containing one of the worst wildfires in Sweden the summer of 2018. To comprehensively address the outcomes of different post-fire management approaches, conducting extensive cost-benefit analyses was the method of this report looking at the core-values; potential for carbon sequestration, economic income, and management costs, as well as societal stated preferences in willingness to pay for terrestrial recreation. The results show that continuous cover forestry provided the highest net present value in the cost-benefit analysis followed by converting to nature reserves and lastly the most common conventional forestry. Continuous cover forestry provided the highest carbon sequestration potential long-term while the highest economic profit was obtained in the conventional forestry. Converting to nature reserve would provide the highest willingness to pay when the nature had adapted to nature-based forest characteristics. The findings in this study suggest that a change in management regimes could be crucial for targeting climate change mitigation work related to wildfires. However, this study concluded that further research is required to obtain more accurate estimates regarding economic aspects and stated preferences to support the outcome of the results.

Populärvetenskaplig sammanfattning

Skogsbränder hotar bevarandet av skogens ekosystemtjänster såsom ekologiska funktioner för biologisk mångfald, mildring av effekter från klimatförändringar och rekreation såsom skogspromenader och bärplockning. Hur kan vi ingripa för att återhämta och bibehålla sådana funktioner i naturen efter bränder? I den här studien undersöktes potentialen för återhämtningen av skogar utifrån skogsåtgärder efter brand baserat på kolinlagring, socioekonomiska preferenser och ekonomiska värden relaterade till aktivt skogsbruk och naturreservat.

Moderna världen idag genomsyras av tekniska lösningar. Vi söker ofta stöd i tekniken för att effektivisera ekonomisk vinningen från olika branscher och spara tid i våra vardagliga liv. Efter skogsbrand är det vanligast att med tekniska redskap kalhugga alla träd och sedan återplantera i stället för att lämna skogen för naturlig återhämtning. Men vad har det för konsekvenser? Den här studien har undersökt ekologiska aspekten av kolinlagring, kostnader och inkomster från skogsbruk och socioekonomiska preferenser för att utvärdera effekterna av alternativa skogsåtgärder efter brand. Studien som använde kostnyttoanalyser visade att kontinuitetsskogsbruk efter brand med naturlig återväxt och småskaliga skogsuttag gav det högsta värdet, följt av konvertering till naturreservat utan tillåtna skogsuttag och sist rangordnades den vanliga kalhyggemetoden. Kostnyttoanalysen sammanställer nyttor och kostnader över en tidsperiod vilket ger möjlighet att jämföra olika effekter i ekonomiska termer. Kostnader för skogsbruk och naturreservat kunde jämföras med ekosystemtjänster och värdesättning av olika naturmiljöer från ett socioekonomiskt perspektiv som annars kan förbises i utvärderingen av olika åtgärder som tas i anspråk. Främst var det att träden fick stå kvar efter branden som bidrog till hög kolinlagring och högre socioekonomiska preferenser för kontinuitetskogsbruk och naturreservat. Däremot fanns det andra fördelar med kalhygge, såsom ökad timmerproduktion, men ur ett övergripande perspektiv var den fördelen mindre gynnsam än de ekologiska och socioekonomiska värderingarna. Naturreservat har fler fördelar som inte inkluderades i analysen såsom bevarandet av biologisk mångfald men det förhindrade skogsbruket i framtiden begränsade inkomsterna som annars hade tillkommit vid avverkning. Slutsatsen som drogs var att det kan finnas ett behov av att förändra det nuvarande systemet av skogsåtgärder efter brand för att mildra effekterna från klimatförändringar samt för att uppnå högre rekreationsvärden. Utvärderingar av resurshantering kan bidra med värdefull information för beslutsfattare och skogsägare kring vilka åtgärder efter brand som ger mest fördelar och vilka skogsåtgärder som kan vidtas för att främja hållbart skogsbruk med avseende på klimatförändringar.

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Abbreviations

CBA – Cost-Benefit Analysis
CCF – Continuous Cover Forestry
CF – Clear-cut Forestry, also called Conventional Forestry
DBH – Diameter Breast Height
FUB – Solid No Bark (Swedish - Fast utan bark)
GPP – Gross Primary Production
GSCC – Global Social Cost of Carbon
HWP – Harvested Wood Products
NEP – Net Ecosystem Production
NPV – Net Present Value
PVB – Present Value Benefits
PVC – Present Value Costs
RFM – Rotation Forest Management, also called CF
SCC – Social Cost of Carbon
SOC – Soil Organic Carbon
WTP – Willingness To Pay

1. Introduction

The forest landscapes provide multifunctional ecosystem services that are crucial for a sustainable future such as food, habitat, storing carbon and for recreational values. Nevertheless, ecosystem services are increasingly put to risk through disturbances from climate change for example flooding, heat waves, drought, and wildfires. Forest fires decrease vegetation, therefore releasing carbon to the atmosphere, damage habitat, and recreational values, as well as negatively affect economic values of timber production. The increase of carbon emissions contribute to global warming and it is in our best interest to understand carbon storage optimum to be able to meet the global temperature target of the Paris agreement (Assmuth & Tahvonen, 2018). Depending on the fire impact severity classes; light/low, moderate and high/extreme fire, the damage to terrestrial ecosystems varies (Kelly et al., 2021). In low severity fires with no tree mortality there is solely a loss in understory vegetation and the soil qualities are affected, while in the moderate or high severity fire there is a partial or complete mortality of the trees and ground vegetation (Kelly et al., 2021). Different post-fire management approaches can therefore affect the potential of recovery and restoration of the ecosystem services after low severity wildfires.

Considering resource management, including post-fire management, is threefold, and should be based on ecological, economic and social aspects (Mavsar et al., 2012). The ecological part includes, the present state, vulnerability to different impacts, and limitations in the development of management objectives. For the economic aspects it can be to evaluate efficiency and distributional effects of feasible management alternatives. Finally, the societal perspective can identify relevant stakeholder groups following their needs, preferences, and conflicts. In resource management, there is often a time lag between management costs and the provisions and value of ecosystem services (Holmes et al., 2008). Evaluations of protection management or resource distribution, requires long time spans and large data gathering efforts as well as careful scientific enterprising (Holmes et al., 2008). A common methodology of evaluating management options is cost-benefit analysis, assessing the relative desirability between options measured as positive or negative changes in quantity or quality of goods, services or prices (Mavsar et al., 2012).

1.1 Background

1.1.1. Forest management practices

Sweden often use the clear-cut (CF) as logging procedure (Lindroth et al., 2018). This conventional forestry work to optimize the harvest for highest economic outcome. Following CF, there is a re-plantation or re-seeding where harvest residues are left to decompose in a process of rotation forest management (RFM) (Peura et al., 2018). An alternative forest practice is continuous cover forestry (CCF), containing un-even aged stands, avoiding the clear-cutting and its initial emissions post-harvest (Lindroth et al., 2018). Instead, the CCF contain selective cutting whereas the potential to deliver and maintain ecosystem services, while conducting a commercial forestry, is considered better than for RFM (Lindroth et al., 2018; Peura et al., 2018). There are different subcategories to CCF depending on the tree species (Skogsstyrelsen, 2023a). Mainly spruce can be harvested through CCF in Sweden but there are projects of development towards similar approaches for other tree species as well (Skogsstyrelsen, 2023a).

In forest areas containing high nature values, the government agencies, Naturvårdsverket and Länsstyrelsen, can forego agreements with private forest-owners to convert forest areas into nature reserves (Länsstyrelsen, u.d). After the fires in Ljusdal municipality, there were fire-damaged boreal forest containing high nature values promoting biodiversity (Länsstyrelsen, u.d). Some of these areas were converted to nature reserves regulating the use and further forest practices for owners who chose to keep the ownership of the land (Länsstyrelsen, u.d). In these areas, landowners had the right to infringement (Naturvårdsverket, u.d.). The compensation right varies dependent on forest size, extent of high nature values, and aggravating or forbidden land use (Naturvårdsverket, u.d.). The infringement right includes the compensation of decrease in market land value with an additional 25% to compensate for expected future income of continued forestry. In some cases, the land can be sold to the government whereas the negotiation can regard both market sales value and loss in future expected income on a case-to-case basis (Naturvårdsverket, 2006).

1.1.2. Carbon sequestration and different forest management

Net ecosystem production (NEP) is described as a difference between carbon input to the ecosystem by gross primary production (GPP) and a carbon loss through respiration (Chapin et al., 2011). A positive NEP corresponds to a carbon exchange with more input of carbon to the ecosystem than carbon loss to the atmosphere (Chapin et al., 2011). Carbon exchanges in ecosystems can be described using carbon fluxes over time in the NEP (Chapin et al., 2011), while the carbon stocks describes the total amount of carbon in the ecosystem. The NEP includes all carbon fluxes from trees, soil, and the understory vegetation in terrestrial landscapes, where trees contain the largest biomasses and therefore large potential to sequestrate CO_2 from the atmosphere. There are also large carbon stocks in forest soils (Clarke et al., 2015). Soil organic carbon (SOC); are carbon stocks in the forest soil with a long turnover-time and the potential for long-term carbon storage (Clarke et al., 2015). After ecosystem disturbances, the carbon being released from the ecosystem SOC to the atmosphere, can increase (Clarke et al., 2015). Depending on the disturbance severity, for example fire severity, the effect on carbon soil can vary significantly (Kelly et al., 2021).

A previous study on carbon fluxes in Canada showed that forests containing harvested or burned forest stands were carbon sources (with a negative NEP) in the 9-17 years following the disturbance (Coursolle et al., 2012). Akao (2011) dicusses the impacts of stand age to carbon storage and found that it depends on which sequestering function were valued most important, sequestering atmospheric carbon or postponing sequestered carbon release. The usage of timber production after salvage logging practices can affect the value of carbon storage (Akao, 2011). Harvested wood products (HWP), that are immediately burned as fuels would release stored carbon to the atmosphere, whereas if harvested wood is used in wood products, then the carbon retention is longer (Akao, 2011; Smyth et al., 2014). Further, other studies found that carbon retention time would be longer if timber production were harvested through CCF since the selective cutting would provide more sawlogs (larger biomass) in proportion to pulpwood than RFM (Peura et al., 2018).

Whether carbon storage is more favourable to continuous cover forestry or cleat-cut forestry is still a question unanswered (Assmuth & Tahvonen, 2018). Assmuth and Tahvonen (2018) writes existing previous studies on forest management practices and carbon storage are either lacking a comparison between management practices or a sound economic basis. However, a previous study conducted by Koriakoski et al. (2023) of partial cuttings, i.e., selective cuttings, in boreal nutrient-rich peatland forests concluded that selective cutting could maintain a constant NEP over time. In difference to the selective cuttings, salvage logging as a post-fire management approach, implies an additional larger disturbance in the ecosystem and will further affect ecosystem services and environmental values in the forests (Kelly & Hodges, 2020). Besides the effect on carbon sequestration, salvage logging post-fire can also negatively impact already fire-damaged habitat for prey species and their predators across large landscapes, and further the recovery of habitat loss which is important for wildlife conservatory (Kelly & Hodges, 2020).

1.1.3. Societal preferences and willingness to pay

As previously mentioned, the public preference of certain management options can reveal and indicate different stakeholder groups within a project or considered management approach (Mavsar et al., 2012). Stated preferences can be measured through willingness to pay (WTP) for terrestrial recreation (Atkinson & Mourato, 2008). These stated preferences are usually the result of survey-based methods to understand the social acceptances to policy changes in a specific site (Atkinson & Mourato, 2008). The stated WTP may differ from actual WTP, often due to an overestimate of economic valuation (Atkinson & Mourato, 2008). In the case of non-site-specific data on WTP, benefit transfer can be conducted where stated preferences in another site is used as secondary data for estimating WTP in areas of interest (Atkinson & Mourato, 2008). However, benefit transfers raise the question of value uncertainty in the site of interest and should be undertaken with acknowledgement of potential transfer-errors related to using secondary data for site-specific estimates (Atkinson & Mourato, 2008; Ready et al., 2004).

1.2. Aim and research question

The global warming contributes to increasing frequency of natural disasters such as wildfires. These disturbances, causes carbon losses from ecosystems, and contributes to increasing greenhouse gas emission. Further, the increased atmospheric CO_2 will enhance global warming in a positive feedback loop. Although knowledge about forests and terrestrial ecosystem services are broad there is still a knowledge gap regarding post-fire management options and their economic outcomes from a societal perspective. Considering ecological benefits in economic outcomes will be important for future development plans, and to be able to reach the sustainable development goals. This study aims to evaluate how different post-fire management approaches affect the ecosystem service of carbon sequestration. Further it aims to investigate the economic and societal consequences from different management regimes. This was done through cost-benefit analyses asking the questions:

1) how will different boreal post-fire forest management affect carbon sequestration long-term?
2) what are the economic and societal consequences from different post-fire management options?

Although forest fires affect multiple ecosystem services that are significant to sustainable living, this report will solely analyse the environmental values of carbon sequestration related to climate change mitigating. This study will include one forest fire and not account for other natural disturbances. Furthermore, the report focuses on low severity fires, the most frequent occurring fire severity in the region of Ljusdal, Sweden, according to Joakim Larsson at Mellanskog (personal communication, April 13, 2022). Finally, due to the size of the report, rough estimates were used to perform the CBAs with the focus of establishing overall differences in the management regimes rather than provide precise estimates on project costs and benefits.

1.3. Ethical reflection

The problematics with monetising ecological features such as ecosystem services indicate putting a maximum value to nature-based benefits that might not be estimated correctly. If they are valued or discounted too low or high, the consequences could be choosing the wrong resource option. Further limitations on which ecological features are investigated also impacts the overall results and are considered as a risk of uncertainty for the project. However, today these analyses are also necessary for the inclusion of ecological services into the development and resource-distribution plans and was therefore done in this report with careful consideration and transparency of chosen limitations, the methodology and how these results were interpreted.

2. Method

Three scenarios of post-fire forest management approaches, listed below, were the basis for the cost-benefit analyses. Scenario 1) and 3) are based on actual forest sites within the Ljusdal forest-complex, which is used as study site for this report, while Scenario 2) contain a fictive scenario of continuous cover forestry with limited or partial cutting. In the analyses, carbon sequestration was compared for the different scenarios. To account for the economic and societal aspects of post-fire forest management approaches, the management profit and costs, and the value of landscape (terrestrial recreation) were included. The scenarios are:

1) The forest area was clear-cut post-fire and the land is privately owned.
2) The forest area became a continuous cover forestry and the land is privately owned.
3) The forest area became a nature reserve, no clear-cutting was allowed.

In this method, the potential of carbon sequestration was quantified based on NEP flux simulations and monetised using the measure of social cost of carbon. The recreational values were obtained from a benefit transfer estimating WTP for forest characteristics in Denmark (Nielsen et al., 2007). The profit and costs were estimated based on general cost and pricing for forestry in Sweden. All monetised values were converted into the same currency and year to perform the three cost-benefit analysis. The cost-benefit analysis summarised all time-flows of previously described core values, through discounting the net present values were obtained, and used to compare the three scenarios in monetised terms. The different steps of the method are described in the sections below. A sensitivity analysis was also included to further investigate the validity of the results.

2.1. The study area of Ljusdal

The forest fire of 2018 in Ljusdal, was one of the worst wildfires seen in a century with 8995 ha burnt area (Kelly et al., 2021). Out of the almost 9000 ha burned area in Ljusdals municipality in Gävleborg county, around 8400 ha productive forest area was damaged in the fires (Eriksson et al., 2018). In the study conducted by Kelly et al., (2021), quantified forest and soil qualities of five forest sites containing *Pinus sylvestris* (scots pine), one growing season after the forest fire. The study showed that disturbance history, stand age and burn severity were important factors for predicting changes in carbon storage for the boreal forest after a fire (Kelly et al., 2021). In some of the areas affected by the Ljusdal fire, private owners chose to salvage log regardless of the fire severity, while in other areas no clear-cutting were conducted because the areas were converted into nature reserves (Kelly et al., 2021). The average stand age of 70 years (in 2018), in the areas studied by Kelly et al. (unpublished), will be the basis for stand age in this report.

2.2. Quantifying the core values

2.2.1 Simulating and monetising carbon sequestration

The carbon sequestration was simulated using the function in Equation (1) below. It's based on a nonlinear regression analysis conducted by Coursolle et al. (2012). Originally this function was used to predict the annual NEP after disturbance for mixed forest in Canada (Coursolle et al., 2012). To adapt the function to the study site of Ljusdal fire-complex, the coefficients of the model were estimated through iterative least square regression, based on the data of pine forest collected by Peichl et al. (2022) and Kelly et al. (unpublished).

$$NEP = a^{(b * age)} + c^{(d * age)} \qquad \text{Equation (1)}$$

Where,
a=316 (g $m^{-2}yr^{-1}$ carbon)
b=-0.0072 (yr^{-1} carbon)
c=-565.8 (g $m^{-2}yr^{-1}$ carbon)
d=-0.0546 (yr^{-1} carbon)
are the coefficients and NEP describes the net ecosystem flux (g $m^{-2}yr^{-1}$ carbon).

For each scenario, the carbon sequestration was simulated based on stand age in a timeline of 150 years. In all scenarios, an estimated initial loss of 430 g m^{-2} carbon in the year of the fire (2018) was included, where the average stand age was 70 years (Kelly et al., 2021). This represents the release of carbon to the atmosphere from soil and understory vegetation (Kelly et al., unpublished). All simulations were performed in R studio R 4.2.1. (R, 2021), and assumed an area of 1 ha. The simulations were converted from carbon sequestered per stand year into the equivalent proportion of CO_2 emissions saved each year (NEP/ (12/44) in ton ha^{-1} yr^{-1}.

In Sweden, the rotation of conventional forestry often occur between stand ages 60-100 (Swedish Forest Industries, 2021). Scenario 1 therefore contained two clear-cuts, the first one directly after the fire and the second at stand age 70 for the new regeneration of forest without the fire impact.

In carbon balance the trees accumulate carbon at the similar rate of which carbon is lost in soil (Korkiakoski et al., 2023). Korkiakoski et al. (2023) studied the impact of partial cuttings to NEP and found that the disturbance by the harvested pine trees and initial limitations in photosynthesis decreased the GPP. However, after 6 years the area became a larger carbon sink than before the disturbance, potentially due to the increase of light exposure, thus the mean NEP remained relatively constant over time. In Scenario 2), the constant NEP from partial-cuttings (Korkiakoski et al., 2023), was assumed. The NEP in Scenario 2) reached the $\mathrm{NEP}_{\mathrm{Max}}$ before the fire in 2018, and after the initial loss at stand age 70 the it immediately recovered to the NEP before the fire. In the Scenario 3), the area was converted to nature reserve, allowing no further forestry. The NEP flux started to decline after the forest reached the $\mathrm{NEP}_{\mathrm{Max}}$, and the carbon sequestration was less and less effective. This was illustrated by the original function in Coursolle et al. (2012) of NEP decline when stand age proceed the $\mathrm{NEP}_{\mathrm{Max}}$. The nature reserve was assumed not to have removal of old trees and anthropogenic regeneration and the simulation were modelled to immediately recover after the fire to its previous state.

To monetise the saved CO_2 emissions through carbon sequestration in ton ha^{-2} yr^{-1} , social cost of carbon was used (Ricke et al., 2018). Social cost of carbon represents the economic damages from the amount of CO_2 emissions released, which is equivalent to the amount of carbon not released to the atmosphere in this report. Ricke et al. (2018) estimated social cost of carbon (SCC) by four distinct components: socio-economic module, climate module, damages module and discounting module. This estimate included future evolution of the economy (with emissions of carbon dioxide), earth systems respond to emissions of carbon dioxide, the quantified economy's response to changes in earth systems as well as a time series of future damages compressed into a single present value. Northern Europe, which includes the boreal forests in Sweden, have negative country level SCC values due to the current temperatures being below the economic optimum for most effective forest growth (Ricke et al., 2018). However, it indicates that releasing carbon emissions to the atmosphere can be considered a benefit in these countries, thus ignoring the shared responsibilities for decreasing carbon emissions on a global scale according to the Paris agreement (Assmuth & Tahvonen, 2018). Hence, an estimate of the global mean social cost of carbon (GSCC) was used to account for the global dimension and external effect of emissions across the world. The study presented a recent expert elicitation of climate scientist and economists mean SCC of US \$150-200 per ton CO_2 (Ricke et al., 2018). A rough estimate of US\$ 175 for SCC was applied to the carbon simulations in this report for all three scenarios, using the Equation (2) below. The dollar value was converted to SEK with the exchange rate 1 US\$ =8.7 (SEK) and included in the CBAs.

$$Benefit\ (\mathrm{US\$}) = CO_2\ (\mathrm{ton\ ha^{-1}}) \times 1373\ \mathrm{SCC}\ (\mathrm{US\$}\ /(\mathrm{ton\ ha^{-1}})) \quad \text{Equation (2)}$$

2.2.1. Benefit transfer of societal preferences

The terrestrial recreation values responding to different post-fire management approaches was undertaken in a benefit transfer based on the study conducted in Denmark by Nielsen et al. (2007). There was a lack of previous studies on terrestrial WTP with both geographical and cultural similarities to Ljusdal, Sweden. Therefore, the Nielsen et al. (2007) was used for this benefit transfer with basis of assumed cultural similarities between Scandinavian countries and the relative closeness in geographics. The study investigated WTP focusing on forest characteristics align with different forest management practices such as variation of tree species, tree height and presence of dead trees left for natural decay (Nielsen et al., 2007). The WTP were measured through a cost factor of increasing annual tax payment per household between 50 DDK to estimated highest price of 1300 DDK for the changes from the base scenario of salvage-logging (Nielsen et al., 2007). The study included the Danish population between the ages 18-75 and contained 548 effective response samples in total. These were gathered through a questionnaire with 27 different forest combinations, simplified in the questionnaire for maintaining the mental capacity of the respondents. The results represent the entire Danish population except that the respondents showed a significantly higher income, employment rates and longer education than the general population. Published results from the questionnaire are summarised in Table 1.

Table 1. Summarising the main results of WTP for forest characteristics (Nielsen et al., 2007)

Forest combination and characteristics	Estimated WTP (DDK)
Mix of conifers and broadleaves	969
Varied tree heights – selective harvest	856
Two heights - shelterwood	205
Few dead trees left in the stand	114
Mixed trees, varied tree heights and few dead trees left for natural decay	1939

The highest WTP was obtained from changing even-aged monocultures of only conifers to the combination of mixed trees, varied tree heights, and few dead trees left for natural decay indicating that nature-based forests were preferred over the conventional forestry (Nielsen et al., 2007). The WTP for such scenario was not presented in the published results although mentioned as 1939 DDK in the discussion (Nielsen et al., 2007). The value was considered over-estimated since the respondents indicated awareness of the change of forest being solely the forest they visited the most and not applied to the total forest area in Denmark (Nielsen et al., 2007). However, the base-case scenario of even-aged coniferous stands where all dead trees are removed, showed the least preference and any change from it resulted in an increase of WTP (Nielsen et al., 2007). Further it was discussed whether the high WTP for nature-based forest characteristics were due to the scenic appeal or ecological knowledge related to ethical beliefs in which the study suggests more research. Hence, this undertaken benefit transfer was used with consideration to its believed sensitivity to demographics and other circumstantial parameters (Nielsen et al., 2007).

Through Nielsen et al. (2007), the WTP for forest characteristics with similarity to the three scenarios in this report were chosen as rough estimates and included in the CBAs. For Scenario 1) the salvage logging practices would provide no dead trees left for natural decay, one tree species and the tree height structure would be a maximum of 2 different tree heights closest comparable to non-mixed forest with two tree height structure (shelterwood practices) (Nielsen et al., 2007). In the Scenario 2) CCF would respond to varies tree heights in Nielsen et al. (2007) from the partial cuttings in this scenario. In Scenario 3), a nature reserve was undertaken which is only feasible for forests with high environmental values (Länsstyrelsen, u.d). Therefore, deciding on the forest characteristics for a nature reserve was more complex. Since the Scenario 3) was turned from a monocultural even-aged forest area to nature reserve, an assumption was made for this scenario. The nature reserve would be complete in its forest complexity gradually until the stand age of 220 (year 150 in the CBA analyses). The same WTP as for Scenario 1) was used for the year 2018 although gradually increasing to the WTP average between mixed forests and forests with varies tree heights in the following 150 years (Table 1.). This estimate was chosen with large uncertainty, yet considered the closest option available from the Nielsen et al. (2007), which was considered important for consistency in demographics between WTP estimates. Few trees left for natural decay (Table 1.) was considered an important forest characteristic although because of the high uncertainty of how to include it this value was not obtained in the CBAs. The WTP for each scenario from Nielsen et al. (20007) was converted to SEK by exchange rate of 1 DDK = 1.235 SEK (2007), and then estimated for 2018 (Statistiska central byrån [scb], u.d.).

2.2.2. Management costs and post-fire timber

There are many costs related to forestry. Therefore, not all can be covered in the report, but overall costs for management and production income was the focus. The timber production profitability varies dependent on management practices applied due to the related costs and HWP (Peura et al., 2018; Tahvonen et al., 2010). The income was estimated based on the harvested volume in solid volume excluding bark (m3 Fub). For 1 tree in Ljusdal the volume in m3 Fub was estimated using the diameter breast height (dbh=0.24 m) and the tree height (h=19 m)(Kelly et al., 2021; Sveriges Lantbruksuniveristet [SLU], 2016), and then converted from forest cubic meter (m^3sk) to m^3Fub by the converter factor 0.85 (Rundvirke Skog, u.d). Lastly the volyme per tree were multiplied by the average total amount of trees per ha 484 in Ljusdal to get the volume per ha (Kelly et al., unpublished).

The HWP ratio between sawlogs and pulpwood is higher in CFF compared to CF (Pukkala, 2014). In this study the ratio assumed was of 90% sawlogs/ 10% pulpwood for Scenario 1) and 93% sawlogs / 7% pulpwood in Scenario 2). The estimated ratios were based on similar calculations of HWP made by Moa Morency, environmental science student at Lund University (M. Morency, personal communication, May 18, 2023), where the field data from fellings of CF and CCF in 2023 were obtained from Djurholmen forest site and provided by Stefan Olsson at Stiftelsen Skånska Lanskap (personal communication, May 11, 2023). The average pricing of sawlogs and pulpwood for 2019 (Skogsstyrelsen, 2023b), were used to calculate the total income per ha of timber production in Scenario 1) and 2), with the ratios of HWP assumed for this report and 484 trees/ha in the study site (Kelly et al., unpublished). The CFF is mainly applied to spruce (Skogsstyrelsen, 2023a) although adapted to pine forest in this report. Consequently, the income of timber production was estimated as 20% (fellings per partial cutting) of total income per ha every 30 years (Skogsstyrelsen, 2023a).

The types of forest species, climate variables and state policies affected what sort of management costs existed in literature. Thus, the average costs for Sweden during 2021 was used in Scenario 1) and 2) (Skogforsk, 2021). Management costs were calculated for the full 1 ha forest in both scenarios since the machinery still needed to operate through the entire area regardless of management regime. The costs from clear-cutting and regeneration were applied for each clear-cut in Scenario 1). Scenario 2), had natural regeneration and no regeneration costs were included. The management costs for CCF in Scenario 2) were repeated every 30 years. All costs in the CBA were included in SEK at its value the year 2018. If they were obtained from values less than two years off the year 2018, they were not converted.

For Scenario 3), management costs nor income from timber production were applicable due to no further management. Nevertheless, the general infringement right of loss in market land value and additional 25% as compensation that should account for the losses in future income from potential continuant forestry are applicable (Naturvårdsverket, u.d.). Several parameters impact the final infringement right and is decided on a case-by-case basis. However, no case data could be obtained for Scenario 3). Still, the inclusion of infringement right was based on the perspective undertaken in the CBAs. From a private perspective the infringement right could be considered a one-time benefit of selling the land with negotiations towards inclusion of future potential income while in a societal perspective it could be seen as a money transfer from the government paying the infringement right to the private owner. The forest sales value in Gävleborg County was in 2022 estimated to 86 000 SEK per ha (Ludvig & Co Fastighetsförmedling, 2022). Further, the additional 25% for the infringement right does not cover the total expected income from timber production in Scenario 1) which will be the basis for the economic set up in Scenario 3). In Scenario 3). the assumption was made that the land was sold to the government for the 2018 sales market value with an inclusion of the additional 25% for the losses in future income.

The difference in the additional 25% of the estimated forest sales value and the predicted future income from Scenario 1), was considered the cost in terms of loss in income for Scenario 3). Regardless, this choice was undertaken with the acknowledgement of high uncertainty.

The economic value estimations did not account for the impact of burned trees on timber production nor market sales value of land area. Expert interviews were conducted to gather such information, however the answers obtained were not sufficient to distinguish value of timber before and after the fire. In an interview with Johan Litsmark at Länsförsäkringar (personal communications, May 17, 2023), Litsmark said that uncertainties arise regarding the utilization of burned timber for timber production due to the sensitivity of sawmills to soot. However, the responses to the interviews were obtained during the later stage of the report writing process and including this information in the analyses would therefore be impractical.

2.3. Creating the cost-benefit analysis

The cost-benefit analysis gathered the quantified marginal effects through the core values above, from the ecological, economic and societal perspectives, and then differentiated the costs and benefits (Mavsar et al., 2012). The quantified core values of saved CO_2 emissions in carbon sequestration, the estimated WTP, and the estimated costs and income, converted into monetised terms of SEK (2018), were used in the CBAs for each scenario, conducted in R studio (R, 2021). First the benefits and costs were presented in time (t) over 150 years. The timelines for the benefits and costs were separately discounted to get the present values of future benefit and costs using the discount rate of 2% ($r = 0.02$) (Perman, 2011). The discount rate of 2% were chosen based on the recommendation for long-term real social discount rate for projects with intergenerational consequences (Drupp et al., 2018). Drupp et al., (2018) also concluded that 90% of the respondents in their report on expert-opinion were comfortable with discount rates varying from 1-3%. Consequently, discount rates 1% and 3% were the minimum respectively maximum values for the sensitivity analysis performed for the CBAs. After the values were discounted all present value benefits (PVB) respectively present value costs (PVC) were summarised separately. The net present value (NPV) was calculated by differentiating the sum of PVB and PVC using Equation (3):

$$NPV = \sum_{t=0}^{150} \frac{B_t - C_t}{(1+r)^t} = sum(PVB) - sum\ (PVC) \qquad \text{Equation (3)}$$

Where,
B = benefits (SEK)
C= costs (SEK)
t= time (years)
r =discount rate (%).

Through the NPV from each scenario, different post-fire management approaches were compared in terms of total cost and benefits over 150 years with start 2018. Finally, the sensitivity of cost-benefit analyses was tested by changing two parameters; the timeline (*t*) and the discount rate (*r*), and thus the insecurity of monetising the ecosystem services could be further discussed.

3. Results

3.1. Flows of costs and benefits

To address the impact of various post-fire management approaches on long-term flows of carbon sequestration, the NEP flux were simulated. Scenario 2) and 3) demonstrate NEP flux for stand ages 0-220 in years to illustrate the assumed NEP history in all scenarios prior to the fire. The removal of all trees in scenario 1) is illustrated by the larger decrease and longer recovery time in Figure 1. Scenario 2) in Figure 2 and Scenario 3) in Figure 3 contain an immediate recovery of NEP after the fire. Moreover, Scenario 1) contain an additional clear-cut that removes all trees and decreases the NEP flux again at stand age 70 in year 2088. The total sum of carbon in each scenario after the fire, calculated by the cumulative sum of NEP over 150 years, showed that Scenario 1) with the two removals of all trees, also had the lowest amount of total carbon stored followed by Scenario 3) and largest carbon storage was held in Scenario 2) (Appendix A).

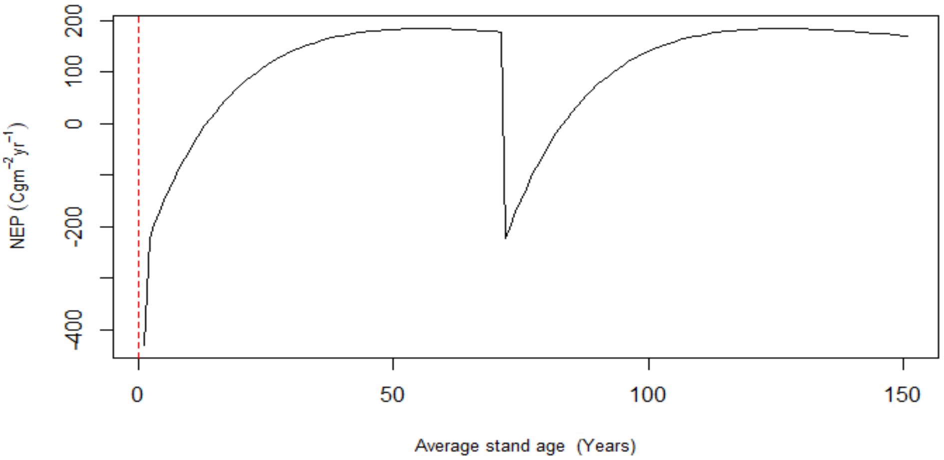

Figure 1. NEP flux Scenario 1. Red line is marking the year of the fire 2018.

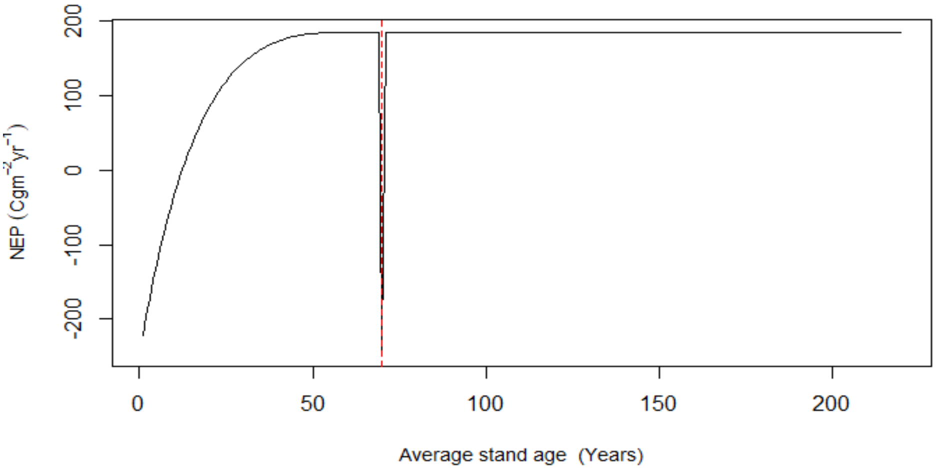

Figure 2. NEP flux for Scenario 2. Red line is marking the year of the fire 2018.

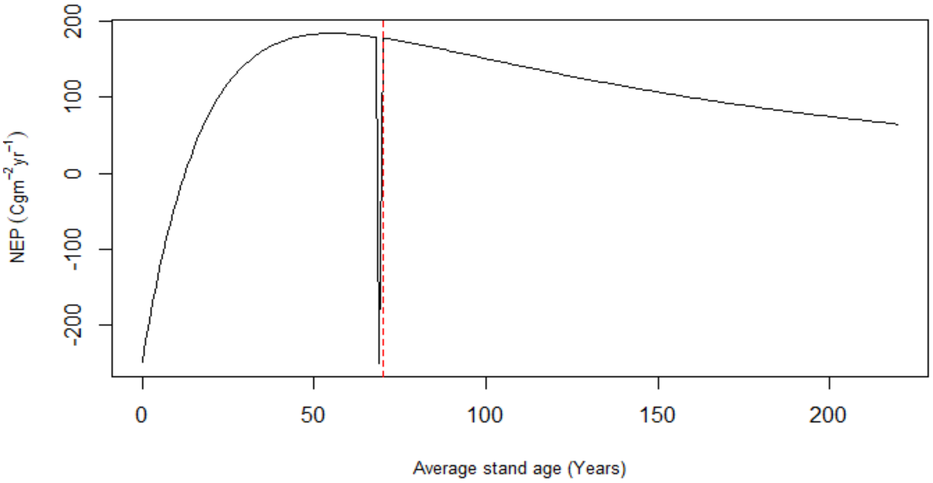

Figure 3. NEP for Scenario 3. Red line is marking the year of the fire 2018.

The benefit transfer for Scenarios 1), 2), and 3) are presented in Table 2. The results for the clear-cut silviculture were not presented in Nielson et al. (2007) and instead the shelterwood practice containing maximum of two tree heights was used. The selective harvest had a noticeably higher WTP than shelterwood. The Scenario 3) transitioned from having the lowest WTP observed in Scenario 1) to becoming a nature reserve with the highest WTP due to the changes in forest characteristics over time. The gradual transformation was applied as a simple linear regression WTP=6.5867*t + 286, where *t* =time in years.

Table 2. WTP from benefit transfer in SEK (2018) (Nielsen et al., 2007).

Scenario	Similar forest characteristics to study site	WTP/year (DDK, 2007)	WTP/year (SEK, 2018)
1)	Shelterwood (max. two tree heights)	205	286
2)	Selective harvest (varies tree heights)	856	1194
3)	The scenario was considered the same as for Scenario 1) prior to the fire. And over time turned into nature-based forest characteristics: Varies tree heights & mix of conifers and broadleaves (2018: two tree heights)	913	from 286 (shelterwood) to 1274 (nature reserve)

The costs for the three scenarios respectively are presented in Table 3. The income of timber and the management costs for Scenario 2) were lower than for Scenario 1), although these were repeated every 30 years (5 times in 150 years). Furthermore, Scenario 1) had a positive difference between income and management costs while the management costs were larger than the income for Scenario 2). The additional 25% infringement right did not compensate for the predicted total loss in income for Scenario 3). No post-fire timber valuation was included for the benefit of income.

Table 3. rough estimates of costs and income SEK (2018), and the economic values from assumption on Scenario 3).

Scenario	Income Benefit (SEK/ha)	Management costs (SEK/ha)	Frequency (total times)
1)	59 489	41 775	2, after the fire, and 70 years later
2)	12 021	18 358	5, every 30 years
3)	Compensation total lost income 20 699	Predicted total loss income 59 489	1

3.2. The Cost-benefit analyses

The conducted CBAs aimed to investigate the societal and economic implications of post-fire management, thereby providing insights of the associated consequences. The net present values presented in Table 4. represents the differences in total present benefits and total present costs for each scenario. The CBAs revealed that Scenario 2) had the highest NPV, followed by Scenario 3) and lastly the Scenario 1) with lower sum of present value benefits and sum of present value costs. The NPV represents the sum of costs and benefits and the changes in net present flows between the years for each scenario are illustrated in Appendix B.

Table 4. summarising the cost-benefit analyses for each scenario in SEK (2018).

Scenario	Timeline (Years)	Discount rate (%)	Sum PVB (SEK)	Sum PVC (SEK)	NPV (SEK)
1)	150	2	229 397	52 219.8	177 177
2)	150	2	532 852	38 882.9	493 969
3)	150	2	351 533	38 790.05	312 743

The sensitivity analysis tested two parameters; timeline sensitivity and discount rate sensitivity (Table 5.). The minimum and maximum values are chosen as extreme values of equal difference to the base timeline and discount rate for the CBAs (Table 4). The table headline row shows the parameter change from the base scenario (Table 5) and table presents the changes in NPV (SEK). Noticeable in Table 5. is that the changes in NPV for different discount rates are significantly larger (in absolute values) than for the timeline parameter regardless of scenario. Nevertheless, the CBAs sensitivity analysis did not affect the ranking of NPV between the three scenarios.

Table 5. The NPV from sensitivity analyses in SEK (2018).

NPV (SEK) Scenario	t_{min}=75 (Years)	t_{max}=225 (Years)	$t_{max-min}$	d_{min}=0.01 (1%)	d_{max}=0.03 (3%)	$d_{max-min}$
1)	129 603	185 468	55 865.0	376 050	86 745.2	-289 305
2)	389 885	492 934	87 649.0	802 018	345 118	-456 900
3)	264 378	323 028	58 650.0	504 181	213 850	-290 331

Overall, the outcome of the results in this study found that Scenario 2) of CCF provided the most beneficial carbon sequestration long-term, Scenario 1) had the largest net income and Scenario 3) would obtain the highest WTP after 150 years. Scenario 2) had the largest NPV with discount rate 2% although the sensitivity analysis suggests that chosen discount rate largely impact final NPV in all scenarios as well as estimated core-values included.

4. Discussion

The aim of this report was to evaluate different post-fire management approaches; conventional forest practices, continuous cover forestry, and converting to nature reserve. The study was conducted through cost-benefit analyses considering the potential of carbon sequestration, economic aspects (practice, products, and costs) and the recreational values in this inter-disciplinary analysis. The CBAs showed that Scenario 2) of CCF had the highest NPV, followed by Scenario 3) of converting to nature reserve and the lowest NPV was obtained in Scenario 1) with clear-cutting post-fire. Scenario 1) had the lowest benefit of CO_2 emissions saved and estimated WTP which strengthen the credibility of this outcome. Although there was a significantly higher income from timber production in Scenario 1) than to Scenario 2) the management costs observed showed a similar trend.

Changing the parameters of discount rate and timeline in the sensitivity analysis of the CBAs affected the NPV in all scenarios. The discount rate provided an almost ten times larger outcome range in comparison to the timeline (Table 5). There was an outlier in the sensitivity analysis when changing the timeline from 150 to 225 years for the Scenario 2), which obtained a marginal smaller value of NPV than for the original timeline. This could have been a consequence of higher costs of management in relation to the profit of timber production. The present value flows are illustrated in Appendix B. to gain further understanding regarding the occurrence of different cost and benefits in the timeline. Hence, the questions of whom the CBAs were conducted for arise. An individual perspective contra a societal perspective can impact which management approach is undertaken regardless of NPV, due to the return of investment. The time-lag between costs and benefits can short-term make some options more attractive than others (Holmes et al., 2008) which is the reason for the timeline sensitivity analysis. The benefits of WTP and carbon sequestration are usually long-term while income from timber production is a short-term benefit and transparency of what perspective the CBA were conducted is considered important.

The substantial differences in NPV from the sensitivity analysis on discount rates, indicated a large parameter impact on the results. Being transparent with the used discount rate is also considered important for the reliability of the outcomes. Nonetheless, different discount rates did not affect the ranking between post-fire management approaches. Consequently, this study showed that CCF obtained the highest NPV in this analysis.

4.1. Analysis of carbon sequestration

The NEP simulation in Scenario 1) with two clear-cuts; one post-fire and the other 70 years after the fire reflects a realistic scenario as conventional forestry rotation typically occurs every 60-100 years (Swedish Forest Industries, 2021). The forest became a carbon source for 13 years after both clear-cuts (Figure 1), aligning with the Coursolle et al. (2012) concluding that salvage logging would turn forests into carbon sources for 9-17 years, and further enhancing the certainty of this simulation. However, in Scenario 2) the carbon sequestration for CCF was modelled based on the assumption of constant NEP long-term from partial cuttings (Korkiakoski et al., 2023). These disturbances were roughly estimated in frequency and volume for spruce and not pine forest and few CCF methods are applicable for pine forests in Sweden today (Skogsstyrelsen, 2023a). Whether that impacted the outcome is still un-determined encouraging further research. There are currently projects developing CCF methods for other tree species (Skogsstyrelsen, 2023a) and for future research this can be used to obtain more precise estimates for the CBAs and enhance the reliability of the results. The study of Korkiakoski et al. (2023) in peat-land soil forest also contained much higher nutrient richness than the boreal forests of Ljusdal (Kelly et al., unpublished) adding to the uncertainty of the outcome in Scenario 2). Thus, the carbon sequestration long-term could be simulated too high in Scenario 2) although by not removing all trees, the ecosystem did not become a carbon source which were the largest negative impact to carbon sequestration in Scenario 1).

Scenario 3), obtained the lowest carbon sequestration (Figure 1). Nonetheless, the total carbon storage was larger than for Scenario 1) by not removing the trees (Appendix A). The CBA may underestimate the benefits of choosing Scenario 3) due to solely measuring changes in fluxes over time. On the other hand, usage of HWP in Scenario 1) also adds to the discussion of total carbon storage. Based on Akao (2011), if the CO_2 stored in HWP are kept in wood products and do not re-enter the atmosphere post-harvest that could offset the negative impact of removing trees in Scenario 1) therefore adding to the carbon benefit by enhancing the carbon sequestration through new generation of trees increasing NEP. Further research is required to investigate the impact of total carbon storage, HWP and for this perspective to be undertaken, where more precise ratios between HWP for timber production should be included in the analysis as well.

No further natural disturbances were included in this analysis after the fire. Mainly this could have impacted the benefit of carbon sequestration in Scenario 3), if disturbances would increase the NEP, such as in the case of partial cuttings in the study conducted by Korkiakoski et al. (2023). No conclusions can be drawn from this argument however further disturbances in future CBAs are recommended to exemplify the reality in a more precise manner. Finally, Scenario 3) provides additional ecosystem services by no harvest, which are not directly related to climate change mitigation. For example, by maintaining habitat and biodiversity after fire through no further disturbances (Kelly & Hodges, 2020), this could increase the benefits of converting to nature reserve in Scenario 3). Including the benefit of habitat restoration to the CBA is also suggested for future studies of forest management-related CBAs to further investigate the resilience of the results in this study. However, the study found that the overall NEP fluxes were highly impacted by the post-fire forest management approach undertaken mainly due to the differences in disturbance severity to the ecosystem between the scenarios and showed that smaller disturbances and no disturbances provided the greater benefits.

Social cost of carbon was estimated to 1373 SEK (year 2018) as a global mean value. The selected SCC impact the benefit derived from carbon sequestration. If the Swedish social cost of carbon (Ricke et al., 2018) was used in this study, the benefit of carbon would be negative and the NPV significantly lower or negative for the scenarios. A positive GSSC in this context aligns with the shared responsibility of the Paris agreement to decrease carbon emissions for climate change mitigation (Assmuth & Tahvonen, 2018).

4.2. Analysis of economic aspects and social preferences

The societal preferences of WTP (Nielsen et al., 2007), provided significant variations across the different scenarios and the sum of WTP greatly impacted the NPVs. The benefit transfer from Nielsen et al. (2007) represents the Danish WTP in 2007. The underlying uncertainty in benefit transfers relate to the potential difference in preferences across demographics, previous topic-related knowledge, and economic background. Moreover, the preferences of 2007 could have been altered over time due to potential changes in cultural appreciation from a societal perspective. The impact of WTP to the analysis could have been wrongly estimated and to increase the certainty of the societal preferences this study suggests a questionnaire of the study site to enhance the probability of representing the current and future generations WTP for terrestrial recreation. Still, there was a clear increase in WTP with any change in forest characteristics that had similarity to nature-based forests (Nielsen et al., 2007). This indicates that the ranking between WTP in the different scenarios are undertaken correctly and support the outcome of the results with highest NPV for nature reserves in Scenario 3), followed by CCF in Scenario 2) and lastly the mono-cultured forests in salvage logging practices (Scenario 1).

Previous studies on carbon storage and forest-practices are undertaken with insufficient economic background (Assmuth & Tahvonen, 2018). This study estimated costs using general profit and management costs data from by Skogstyrelsen (2023a) and Skogforsk (2011) providing an overview of differences in costs and income from timber production between the scenarios. From a solely economic perspective, clear-cutting post-fire in Scenario 1) generated the highest economic benefit in relation to the management costs. However, the regional variations in climate affect the management cost and profits. By not using site-based data for economic valuation there are uncertainties if they differ significantly between sites. For example, the ratios between HWP from fellings were estimated from the Djurholmen forest site in south of Sweden (S. Olsson, personal communication, May 11, 2023) and may be different from the Ljusdal forest site in Gävleborg County. Furthermore, Scenario 2) of CFF was a fictive scenario which did not occur in the forest site and management was based on CCF for spruce (Skogsstyrelsen, 2023b). Therefore, the economic valuation of these post-fire management approaches does not provide specific outcomes of economic benefits and costs related to the forestry undertaken. In the conducted CBAs this mainly affects the NPV for Scenario 1), where the economic costs and benefits were the dominant parameters. Scenario 1) could have been underestimated from an economic perspective. Although, as previously mentioned this study was limited to ecosystem services of carbon sequestration, timber production and recreational values and investigating further ecosystem services can impact which parameter were the dominant one. In Scenario 2), the outcome was more reliable due to the sum of WTP, and the sum of carbon benefit that were by far the dominant parameters. Still, more precise cost estimates are suggested to support this argument mainly by further research of CCF methods for pine forests. Scenario 3) of converting into nature reserves are based on case-to-case negotiation and the assumptions were mainly estimated by general knowledge regarding infringement compensation and market sales value (Ludvig & Co Fastighetsförmedling, 2022; Naturvårdsverket, u.d.). Using a case negotiation from converting forest area into nature reserve in Ljusdal would offer a more precise estimate for this scenario. However, the outcome of Scenario 3) showed a general distribution regarding costs and benefits over time.

The impact of burned timber could not be included in the analysis due to time constraints and insufficient information. Nonetheless, Litsmark at Länsförsäkringar (personal communication, May 17, 2023) discloses the uncertainty of utilising forest burned timber in timber production due to the sensitivity of sawmills to soot, which suggests that the income of timber would be negatively impacted in areas with active forest management. This especially in Scenario 1), where all the trees were clear-cut post-fire. Overall, more precise estimates of economic profits and costs would increase the certainty of the results, nevertheless the inclusion of general economic aspects still provides insightful information regarding the consequences in different management options from an economic perspective.

5. Conclusion

The post-fire management approaches can have a large impact on climate change mitigation after the release of CO_2 through wildfires. Key findings in this report show that CCF obtained the highest WTP and largest potential of carbon sequestration long-term. Further the profit of timber production was higher in CF than for CCF and the compensation for lost future income and sales value from the converted nature reserve did not enhance the profitability of that scenario in relation to the active forest management approaches. This report, although in need of more precise values, indicates that a transformation from the conventional forestry of clear-cutting to post-fire forest management with smaller disturbances can be crucial to maintaining ecosystem services such as carbon sequestration. Even though nature reserves with no management allowed did not provide the largest NPV it preserves other important ecosystem services, for example habitat, which are disturbed in active forest management. Further studies including such parameters are suggested before considering this option as the less profitable forest option. To maintain and enhance the ecosystem services that provide climate change mitigation, considering different management options for resource distribution is crucial and there is an important gain in choosing the option that provide these. Finally, future research on post-fire related management approaches is suggested to provide support for the outcome of the results in this study.

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7. Appendix

Appendix A – Cumulative NEP

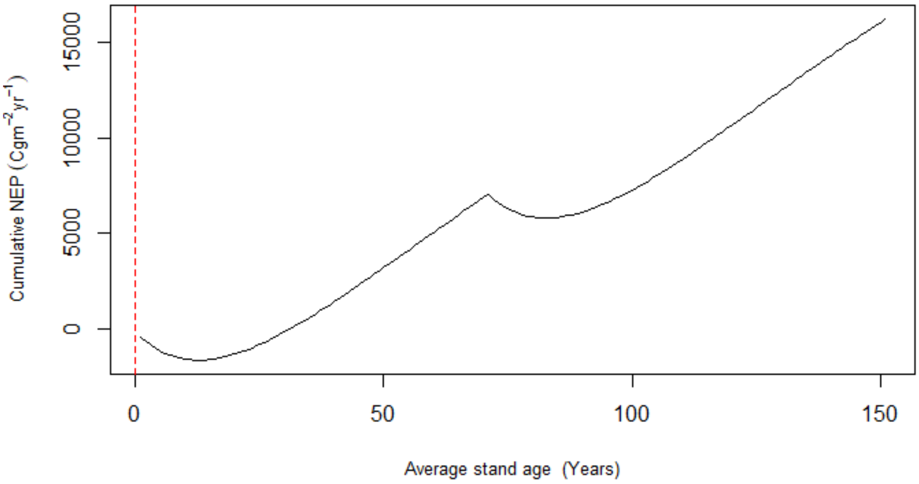

Figure A 1. Cumulative NEP Scenario 1. Sum of carbon stock = 8696 (ton per ha). Red line marking the year of the fire 2018.

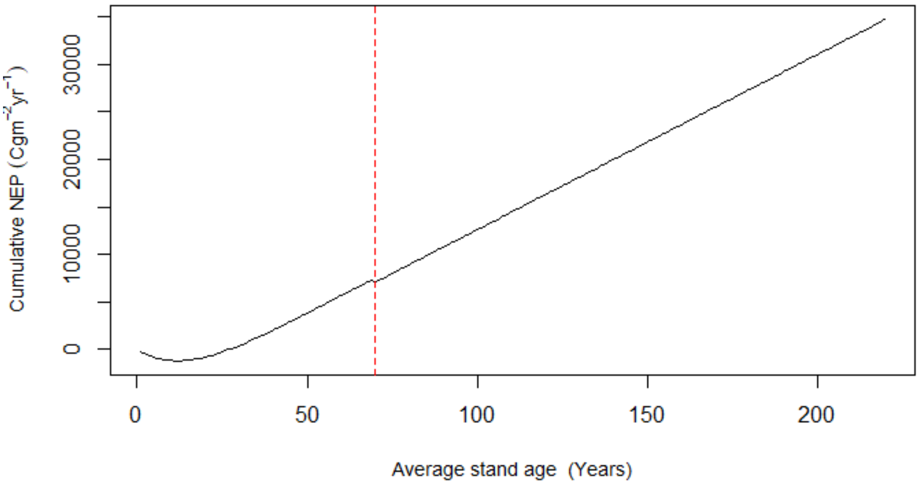

Figure A 2. Cumulative NEP Scenario 2. Sum of carbon stock = 31 560 (ton per ha). Red line marking the year of the fire 2018.

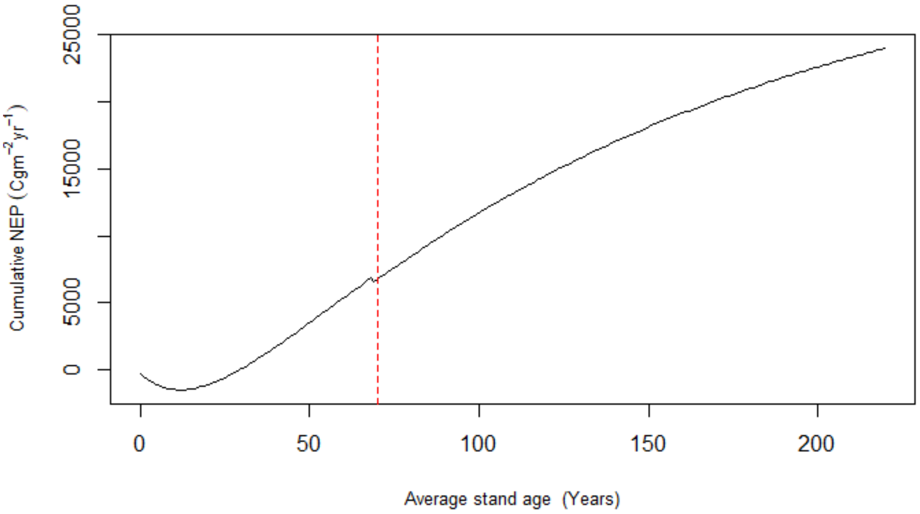

Figure A 3. Cumulative NEP Scenario 3. Sum of carbon stock = 25 242 (ton per ha). Red line marking the year of the fire 2018.

Appendix B – Present value flows

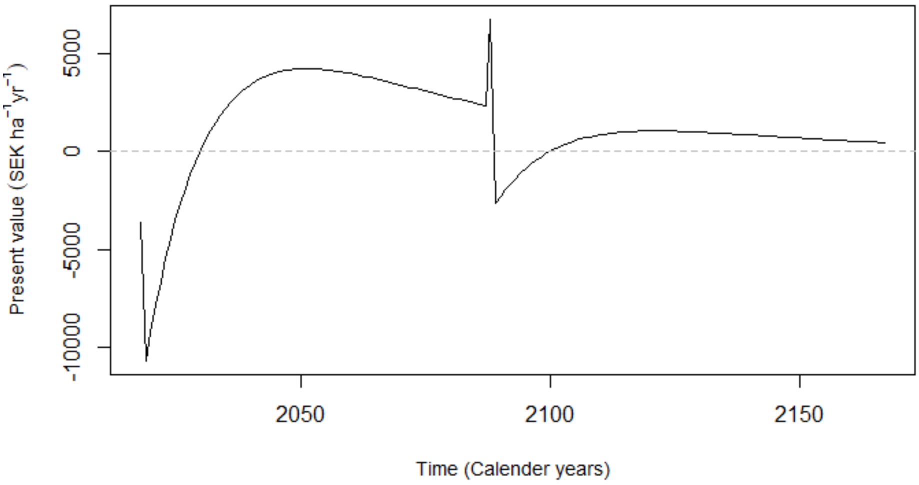

Figure B 1. Present value flow for Scenario 1.

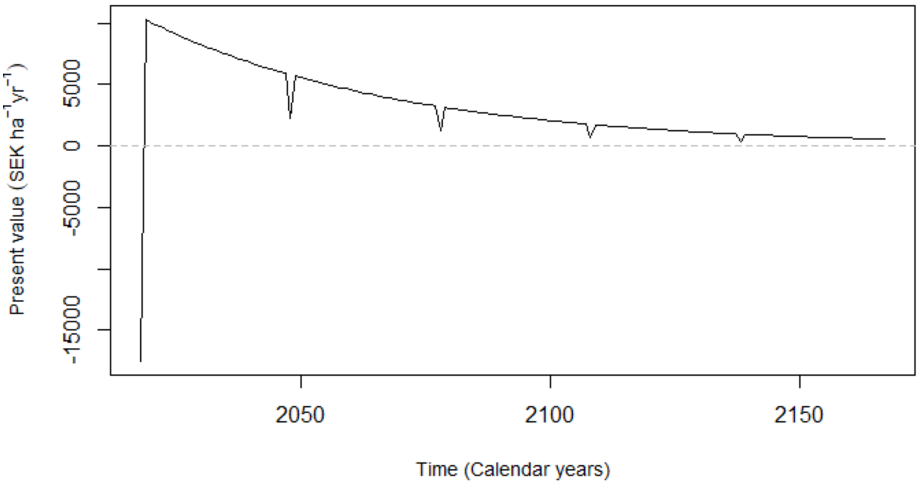

Figure B 2. Present value flow for Scenario 2.

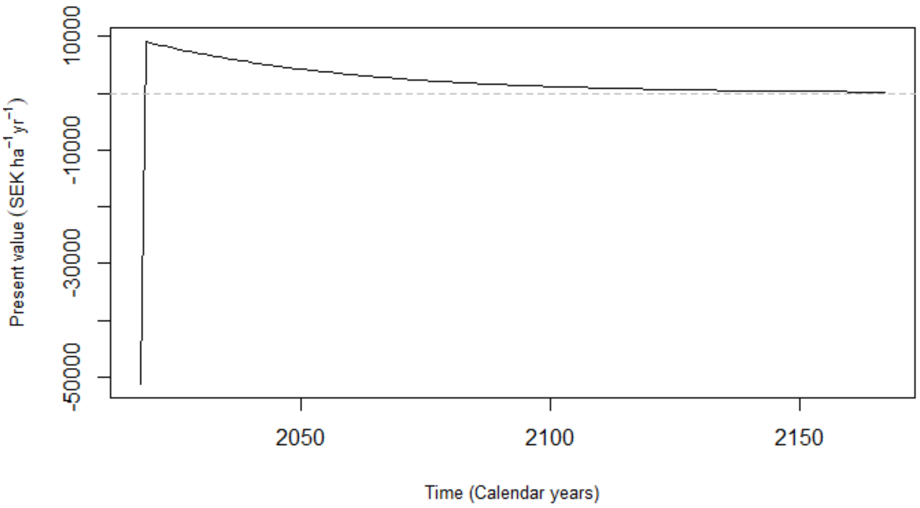

Figure B 3. Present value flow for Scenario 3.